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PHOTOGRAPHIC OBSERVATIONS OF DANIEL'S COMET.

(PLATES I–XXV.)

BY E. E. BARNARD.

(*Read April 25, 1908.*)

It is such a long time since one has had the opportunity of seeing a large comet that the sight of this beautiful object suspended in the quiet summer morning skies with its slender graceful tail streaming upwards into the night, was something long to be remembered. It was a very impressive picture and those who were fortunate enough to see it at its best must have been struck with its quiet and majestic beauty. This was specially the case for a few mornings in the middle of August when the moon was absent, and as late as the first week in September when, though very low in the east and visible only for a few minutes before dawn killed it, the tail could be traced for a distance of fifteen degrees or more.

This comet was discovered by Mr. Zaccheus Daniel at Princeton, N. J., on 1907, June 9. Though it proved to be one of the brightest comets that have appeared in the past twenty-five years, it was in some respects a disappointing object—disappointing only, however, in the want of new phenomena. It was visible to the naked eye for two full months. At one time its tail attained a length of twenty-five degrees. Shortly after perihelion passage—when last seen in the

morning sky—the nucleus was as bright as a first magnitude star. Singularly enough, the comet developed its most interesting changes a month or more before perihelion passage. When near perihelion, which occurred September 3, there were few changes in its appearance from morning to morning. At that time there seemed to be a uniform unbroken flow of the tail-forming particles, so that what streams there were, were not individually prominent or striking.

In the second half of July separate streams of matter were frequent and formed a most interesting feature of the tail. These were specially beautiful on July 17 and 19. On the first of these dates the tail, where it joined the head, was made up of some five broad, diverging streams, which gave it a splendid and symmetrical appearance. This is really the handsomest photograph I have ever seen of a comet.

Comparatively few observatories obtained photographs of this comet, which was a great pity, for it was worthy of far more attention from a photographic standpoint than it received. Several, however, succeeded in getting results that are important. Excellent photographs were obtained by Mr. W. A. Cogshall at the Kirkwood Observatory at the State University, Bloomington, Indiana, with a small reflecting telescope made by himself. Though these, from the limitations of the reflector, do not show a great length of tail, they are specially beautiful and valuable for the structural details. A good series was also obtained at Greenwich. Dr. Max Wolf secured some specially valuable photographs with the 30-inch reflector, whose large scale showed the tail near the head, on several dates, to be made up of a great number of thin rays.

An excellent series of photographs of the comet was made by Mr. Duncan at the Lick Observatory. Though the time interval between these last and those of the Yerkes Observatory is roughly only two hours, there are decided changes shown in the tail when these pictures are compared with those made at the Yerkes Observatory. Unfortunately the changes in the comet are such that there are no definite markings that can be measured on the photographs to determine the motion of the tail-producing particles, with perhaps one exception—that of July 11. There are twelve dates that

are common to the Lick and the Yerkes plates. Several of the Yerkes photographs show very little on account of clouds and thick sky on the dates in question.

Another fine series of photographs of the comet was made by M. F. Quénisset of M. Flammarion's observatory at Juvisy, France. The interval of some six hours makes this series specially valuable for comparison with plates taken in this country. I am greatly indebted to M. Quénisset for enlarged prints from eleven of these pictures. Out of these, there are eight dates which were duplicated at the Yerkes Observatory. A comparison of these photographs is of extremely great interest, and though there is but little material from which to accurately determine the amount of motion, progressive outward displacement, especially in the streamers, is strongly shown. A study of these photographs clearly shows how uncertain it is to connect the details of any two dates. Of course a disturbance may extend over several days and the matter from it still be visible, but any particular detail would not probably live through from one date to another. In some of M. Quénisset's photographs the change has been so great that it is almost impossible to be sure of the same features six hours after. What is quite evident, however, in the comparison, is that the structure of the tail (the streamers) has a decided outward motion as a whole; at the same time there is a diffusion effect that constantly tends to destroy the details.

Some of these comparisons follow:

July 19, Juvisy Plate.—There is a principal narrow ray that separates into two rays some distance out. A dark space intervenes between it and a broad streamer south, whose north edge is very definite. There is a very decided change shown in the Yerkes photograph. Two new short rays have appeared on the south side. The north ray has become broad and diffused and irregular. The changes are so striking that one can hardly be sure of the same features, though there is a general resemblance.

August 11.—In the Juvisy picture there are four distinct rays. The two middle ones diverge from a point close to the head. These two are clean cut in the Yerkes plate. The south one has become

much brighter and more definite. Their junction has bodily moved outward for quite a distance. The north ray of the four has closed in on the one close south of it. A broad light region on the south edge of the northern of the two middle rays has drifted outwards and is less marked.

August 14.—There is one broad widening stream in the Juvisy photograph, with two lesser ones symmetrically placed on each side. In the Yerkes plate there is a general resemblance to the other; though the tail is made up of three broad streamers, they are much further out. It looks as if the three had drifted out and fused together more or less. The whole system of tails has bodily receded from the comet.

August 19.—In the Yerkes plate the head has become relatively smaller. The tail has spread out very greatly, especially on the south side. There is less structure than in the Juvisy plate.

August 20.—In the Juvisy plate a principal ray divides to the north and joins a dark space behind the head. In the Yerkes plate this ray and dark space have both moved outwards. The head and neck are also narrower.

On July 11 (which date we will treat specially) a bright condensation $1\frac{1}{4}°$ back from the head is strongly shown on both the Yerkes and Lick plates and can be seen on the Juvisy plate, but it is faint and cannot be located with very great accuracy on this last picture. A plate made at the Lick on July 10 seems to show this same object somewhat nearer to the comet or about $\frac{3}{4}$ as far out as on the eleventh. It is noticeable on all three photographs of July 11 that this condensation was receding from the comet, at the same time that it was following slowly towards the sun. From the appearance I am inclined to think that it is the same object which is visible on the plate of July 10. If so, then it must have left the comet on or about July 7. Between this condensation and the head of the comet on July 11 the tail is very faint but continuous. In reality this mass is the near end of a bright strip of the tail about 3° long. The object on the Lick plate of July 10 is joined to the head by a bright, strongly defined connection, of which the condensation is only an inconspicuous part. In the interval between July 10 and

11 the mass (if the same) had increased its distance from the head by about 20′. In the meantime it had drifted sunward 1° 10′—following in the direction of the comet's motion. It is probable that this was due to its original motion when a part of the comet, and that if its existence had been permanent enough, the motion would have become one of recession from the sun, but it rapidly dissipated before other photographs could be made of it.

With the aid of the BD charts I have taken off the following positions on the photographs of July 11:

	Position of the Head 1855.0.	Position of the Condensation 1855.0.
Juvisy,	$1^h\,48^m.05 + 8°\,12'$	$1^h\,44^m.0 + 7°\,54'$
Yerkes,	$1^h\,49^m.50 + 8°\,19'$	$1^h\,45^m.0 + 7°\,53'$
Lick,	$1^h\,50^m.05 + 8°\,18'$	$1^h\,45^m.0 + 7°\,54'$

The position angles of the mean axis of the tail on this date are:

Juvisy,	P. A.	251°.5
Yerkes,		251°.5
Lick,		251°.0

If one should take the brighter, long part of the tail, independent of the head, the axis of it would pass a little north of the head.

The following positions were taken off by the aid of the BD charts on the plates of July 19.

Juvisy.—Position of the head 1855.0 $2^h\,40^m.50 + 11°\,29'$. Position angle of the middle long, bright branch of the tail 249°.2. The main or central branch separates at 37′.7 back of the head. The south branch of the tail is 5° less in position angle than the middle one.

Yerkes.—Position of head 1855.0 $2^h\,42^m.67 + 11°\,33'$. Position angle of main branch of the tail (n. of 2) 253°.5. The south one was in P.A. 250°, but was irregularly curved.

Lick.—Position of head 1855.0 $2^h\,42^m.50 + 11°\,32'$. Position angle of main and largest branch 252°.9.

The following are the positions on August 11, derived from the charts.

Juvisy.—Position of head 1855.0 $6^h\,4^m.70 + 17°\,23'$. Position

angle of south ray 257°.0. Position angle of north ray 270°.0; not extreme north ray.

Yerkes.—Position of head 1855.0 $6^h\ 7^m.10 + 17°\ 23'$. Position angle of south ray 259°.0; assuming center of head as origin. Position angle of north ray 269°.0; assuming center of head as origin.

On a number of mornings I carefully examined the comet with the 40-inch telescope and its 4-inch finder. In the great telescope the view was not satisfactory because of the very small field — $5\frac{1}{2}'$ of arc. It showed the nucleus, however, and part of the head very well. The view in the finder was very much more satisfactory, but even this was a disappointment. The nucleus and head and part of the tail were very beautiful. The soft nebulous light of the comet with the bright yellowish star-like nucleus imbedded in the head made a very striking picture. But there were no details visible in either the head or the tail. The streamers which were shown on the photographs at about the same time could not be seen. Viewing the comet thus and then afterwards seeing the photograph of it, impressed one greatly with the value of photography in dealing with these objects. I think most of the phenomena of this comet would have passed away unknown had it not been for the photographic plate.

Notes on the Appearance of the Comet with the Naked Eye, with the 5-inch Guiding Telescope and with the 40-inch and its 4-inch Finder.

July 15.—The comet was visible to the naked eye as a hazy star of the fourth magnitude. It was decidedly brighter than the Andromeda nebula, but much smaller. It was $\frac{1}{2}$ magnitude brighter than the star 3° east of it, BD + 9° 316 (1855.0 $2^h\ 17^m\ 3^s.0 + 9°\ 57'.9\ 5^m.7$). While guiding it seemed to fade for short intervals—perhaps this was due to thin patches of clouds, though I could not see any clouds.

July 17.—Bright to naked eye. It was $3\frac{1}{2}$ magnitude. Very much like a considerable hazy star. Could faintly see a very slender tail for 5°± which passed several faint stars 4° from the head. The comet was $\frac{1}{2}$ magnitude or more brighter than the fourth mag-

nitude star, BD + 7° 388 (1855.0 2^h 20^m $27^s.7$ + 7° 48′.4 $4^m.5$), 4° ± south of it. It was brighter than any of the stars near.

July 18.—To the naked eye, when best seen—visible only through gaps in clouds—the head was third magnitude. It seemed to be brighter than on the seventeenth.

July 19.—I am sure there were frequent fluctuations of the comet's light to the extent of about one magnitude. To the naked eye the comet was 3½ magnitude. At best it was ½ magnitude brighter than the naked eye star, BD + 9° 359 (1855.0 2^h 37^m $6^s.0$ + 9° 29′.9 $4^m.0$), 3° s.w. of it. Could see faint suggestions of a tail. Good sky.

July 28.—15^h 45^m. The head was conspicuous, like a hazy star, notwithstanding a gibbous moon. In the finder of the 40-inch I could trace the tail faintly across the field (2°). There was a bright stellar nucleus of about the sixth magnitude. In the 40-inch the nucleus was very bright, but not stellar. The head filled the field of view (5½′ power 460). There seemed to be a shadow effect behind the nucleus—away from the sun.

July 31.—In spite of the presence of a half moon the comet was conspicuous, like a hazy star, 2° west of Aldebaran. I could see it with the naked eye as late as 16^h 3^m.

August 1.—The comet was conspicuous, like a bright hazy star. It was the same brightness as δ^1 or δ^2 Tauri. Could not be certain of any tail. In the guiding telescope the nucleus was not so distinct as it was on July 31.

August 3.—It was conspicuous like a small 3 or 3½ magnitude star. There were faint suggestions of a tail to the naked eye. It was not decidedly brighter [than on the first]. There was, of course, less moonlight than on the other morning. In the 5-inch the nucleus was not definite—only a central condensation. There seemed to be fluctuations in its light with the 5-inch and I think they were verified with the naked eye.

August 5.—To the naked eye the head of the comet was equal to ζ Tauri. The tail was about 15° in length and stretched out to within a degree or two of Aldebaran. At times I thought I could see it as far as Aldebaran. It would have passed south of that

star and was fairly distinct. The comet was a conspicuous object to the naked eye.

August 6.—With the naked eye the head was as bright as ζ Tauri. Could trace the tail, which was conspicuous but not bright, as far as Aldebaran, where it passed south of that star; it was neither slender nor broad—and seemed to be straight. With the 40-inch the nucleus was not stellar but was bright and yellowish. It was blurred or ill defined in the direction of the sun—apparently spread out—while on the opposite side (away from the sun) it was quite definite wtih a darker space in the nebulosity. The head was much larger than the field of view. In the finder, the tail stretched away across the field. There was a sixth magnitude yellowish star in it, about $\frac{1}{2}°$ back from the head. There was no detail or structure in the comet as seen in the 4-inch finder. The nucleus was about the fifth magnitude and almost stellar. The tail was very slender. The edges were soft and roundish—like a cylindrical or conical body. It was very beautiful in the finder.

August 8.—To the naked eye the tail seemed to be almost the same as on the sixth and was not sensibly longer, but the head was brighter. The comet was $\frac{1}{2}$ magnitude brighter than ζ Tauri and about equal to θ Aurigæ. The sky was good. With the 40-inch the measured diameter of the nucleus at $16^h\ 7^m$ was $2''.49$. This gives a diameter of 2,580 miles. It was slightly yellow. There was a sharp outline several minutes long nearly straight, which passed the preceding edge of the nucleus and which bounded a much denser nebulosity following, in which the nucleus was immersed. The position angle of this definitely bounded nebulosity was $160°.6$ (1) at $16^h\ 8^m$. In the finder the nucleus was stellar and bright. The comet was still faintly visible with the naked eye at $16^h\ 19^m$, but at the limit of vision on the dawn-lit sky.

August 9.—Sky not very transparent. The tail was not so conspicuous as on the eighth; the head seemed brighter, however. It could be faintly traced to a distance as great as that from ζ Tauri to Aldebaran (16°). The head was somewhat less bright than λ Orionis.

August 10.—Sky very good. To the naked eye the comet was

bright for some 3° or 4° back from the head. The nucleus was visible to the eye as a star of about the third magnitude. The head was midway in brightness between that of ζ Tauri and λ Orionis. The tail could be traced faintly for at least 15°. It was pretty faint but when looked at with averted vision it could be seen fairly well for a distance equal to that from ζ Tauri to Aldebaran. The end of the tail just reached to BD + 15° 732 (1855.0 4^h 56^m $18^s.0$ + 15°12′.3).

August 11.—The tail, with the naked eye, could be traced to BD + 15° 732. The south edge would pass through that star. It was 1° or 1½° wide at that point. Though faint, it could be seen quite well. It was straight and somewhat narrow. The nucleus was conspicuous as a star-like body in the head. The head itself was narrow. The tail was bright for 2° or more and then it faded out rapidly towards the end. The head was as bright as η Geminorum. In the 40-inch the nucleus was ill defined, and blurred into the brightness following. It was distinct at the preceding edge.

August 12.—Sky first-class. With the naked eye the nucleus was bright and stellar. It was about as bright as η Geminorum. The tail was perhaps a little brighter than before but rather feeble except near the head. I could trace it faintly nearly to BD + 15° 732. The head was as conspicuous as γ Geminorum, near and to the east, but the nucleus was much less bright than that star.

August 13.—The sky was very thick, and part of the time at first the comet was behind clouds.

August 14.—Clouds at first covered the comet. It then came out and was conspicuous about 2° east of γ Geminorum. When the comet and star came out of the clouds they were very much alike, but as they rose higher the stellar condition of the nucleus was much inferior to the star—say 1 magnitude less bright. The tail was straight and rather slender. For 5° back of the head it was pretty bright, then for the rest of its length it was faint. It could, however, be readily traced to 126 Tauri (Proctor's chart).

August 19.—It was bright to the eye—perhaps brighter than before. The tail could not be traced far—perhaps nearly to γ Geminorum. Sky very poor.

August 20.—With the naked eye the comet was a very graceful and beautiful object. The tail could be faintly traced to about γ Geminorum. The nucleus was star-like and bright.

August 21.—After the nearly full moon set, the sky was still affected by moonlight when dawn began. At $15^h\ 30^m$ or $15^h\ 40^m$ the comet was bright. The nucleus was bright to the eye and was perhaps of $2\frac{1}{2}$ magnitude. The head was not as conspicuous as γ Geminorum—but not much inferior to it.

August 22.—Full moon. The head and nucleus of the comet were conspicuous in spite of the moonlight. The nucleus was about $2\frac{1}{2}$ magnitude. The tail was noticeable or conspicuous for 3° or 4°. In looking in its direction one would have been impressed with its distinctness.

August 24.—Nearly full moon. Sky clear. The comet was conspicuous. Even in the bright moonlight I could see the tail for 4° or 5°.

August 25.—In clouds and haze.

August 31.—Sky good and clear. Crescent moon. The comet was fairly noticeable to the naked eye when its place was known. Could feebly trace the tail for 4° or 5°.

September 2.—It was conspicuous to the eye with a tail 4° or 5° long even in the strong moonlight. The nucleus was about 2 or $2\frac{1}{2}$ magnitude.

September 5.—The comet was very low but the head was bright. The tail, though not bright, could be traced for 14° as drawn on a star chart. It was long and straight and gradually faded out to the end. The sky was fairly good, but as dawn came up some masses of haze were visible in the east. It was estimated that, to the eye, the head and nucleus were about third magnitude. Very slender crescent moon near horizon.

September 8.—To the naked eye the nucleus was as bright as a first magnitude star. The tail could be traced 5° or 6° but partly hidden by clouds.

September 11.—The comet was very low. The nucleus was fairly distinct to the naked eye, but there was only a suggestion of a tail. It had faded very much since the eighth [due to its low position?]. Sky lit with dawn.

September 12.—I could not see it with the naked eye though I tried hard. Not bright in guiding telescope. Sky not pure. Strong dawn.

The photographs taken here of this comet were made with the 10-inch, the 6.2-inch and the 3.4-inch portrait lenses of the Bruce telescope of the Yerkes Observatory. The plates used were Seed 27 Gilt Edge. They were backed with a dark red paste made of burnt sienna and caramels.

Much trouble was experienced from cloudy weather and bad skies. Every opportunity was taken advantage of, however, to secure photographs of the comet. I am greatly obliged to my friend Dr. S. A. Mitchell, who guided for me on several mornings that work with the large telescope would otherwise have prevented photographs being secured. On a few mornings Dr. Mitchell attached his small camera with a Goerz double anistigmat lens of 1¼-inch aperture and 6-inch focus $\therefore a/f = 1/4.8$, on to the Bruce mounting, and secured some negatives which showed a greater length of tail than was possible with the other lenses.

Following is a list of the photographs made with the Bruce telescope:

In the column marked "Lenses," *a* is the 10-inch Brashear doublet, *b* the 6-inch, *c* the 3.4-inch and *d* the 1¼-inch Goerz lens.

In conclusion it would seem that we have to deal with several different kinds of physical phenomena in the study of comets. These are doubtless closely related and are probably the same phenomena acting under different conditions.

There is the regular production of the tail through the repellent action of the sun's light. The tail forming particles in this case will be very small. They may go out from the comet as a broad stream or they may produce several streams more or less narrow. The direction of these various rays are dependent, to some extent, on an exciting and directing force in the comet itself, but the general direction will be more or less influenced by light pressure. These streams, or rays, will be more or less uniformly straight or curved—almost always straight or nearly so. They may be broken or abruptly deflected but this will be due to some influence encountered

in their progressive motion in the general direction of the comet's flight. Such streams will more nearly represent the true emissive velocity of the particles. I have shown in the *Astrophysical Journal*, Vol. XVIII., p. 214, in the case of Borrelley's comet, that the tail of a comet actually moves forward bodily as a whole both outward from the sun and progressively in the direction of the comet's mo-

List of Photographs of Daniel's Comet Made with the Bruce Telescope.

Approximate Position 1855.0.

		α	δ	Cent. Stan. Time.	Duration of Exposure.	Lenses.	
		h. m.	° ′	h. m.	h. m.		
June	20	0 18	+ 1 20	14 23	0 45	a b	
July	3	1 8	+ 5 15	14 6	1 2	a b	
	11	1 49.5	+ 8 20	13 58	2 12	a b c	
	13	2 1.5	+ 9 6	14 7	1 55	a b c	
	15	2 14	+10 0	13 52	2 20	a b c	
	17	2 27.5	+10 40	13 59	2 10	a c	
	17	2 27.5	+10 40	14 27	1 14	b	
	18	2 35	+11 10	14 7	1 50	a b c	
	19	2 42	+11 32	13 54	2 18	a b c	
	20	2 50±	+12 0±			a b c	
	29	4 6	+15 30	14 41	1 40	a b c	
	31	4 24	+16 0	15 2	1 17	a b c	
Aug.	1	4 33	+16 9	14 46	1 45	a b c	
	3	4 53	+16 40	14 53	1 40	a b c	
	5	5 11	+17 5	15 8	1 6	a b c	
	6	5 21	+17 10	15 3	1 21	a b c	
	8	5 39	+17 22	15 30	0 33	a b c	
	9	5 50	+17 20	15 1	1 32	a b c	
	10	5 58	+17 25	14 57	1 43	a b c	
	11	6 7	+17 25	14 59	1 42	a b c d	
	12	6 16	+17 25	15 7	1 43	a b c d	
	13	6 25	+17 20	15 8	1 11	a b c d	
	14	6 34	+17 20	15 11	1 20	a b c d	
	17	7 0	+16 55	15 10	1 30	a b c d	
	19	7 16	+16 30	15 40	0 40	a b c d	
	20	7 24	+16 30	15 27	1 5	a b c d	
	21	7 33	+16 30	15 36	0 50	a b d	
	22	7 39	+16 5	15 40	0 44	a b c d	
	23	7 47	+16 0	15 45	0 40	a b c d	
	24	7 54	+15 40	15 48	0 34	a b c d	
	25			15 23	0 5	a b	
	29			15 45±		a b c d	Few min. only, clouds
	30			15 55		a b c d	" " " "
	31	8 45	+14 20	15 59	0 39	a b c d	
Sept.	2	8 58	+13 10	15 51	0 18	a b c	
	5	9 18	+12 30±	16 0	0 37	a b c	
	8	9 34	+11 20	16 17±	0 5±	a b	
	11			16 19	0 24	a b c	
	12			16 25	0 20	a b c	

tion, and that some of the particles must move outward from the sun very much faster than others of the same stream. This was shown in the formation of the new tail of the above-named comet on July 24. In the tail on that date the later photographs showed that the end of the new tail was increasing its distance from the head much faster than the end of the receding disconnected tail. But in this case the conditions were different; the supply of matter forming the outgoing stream had suddenly been stopped and the stream itself continued to move out bodily into space until it was dissipated. The apparent velocity was then the velocity of the stream of particles. In the case of Daniel's comet a denser mass of particles differing from the general streams that formed the tail was separated from the main body. This would naturally leave the comet slowly and continue to partake of the original motion. Still another case was that of Brook's comet of 1889 (comet V., 1889) where the masses thrown off were so dense that they traveled with the parent comet for months as individual companions before finally disappearing.[1] And yet another case, that of Biela's comet which separated into two masses that remained individually distinct for some years and then entirely disintegrated. The motion of a dense mass thrown off from a comet would not therefore be a criterion for the determination of the velocity in general of the particles of the tail of such a comet.

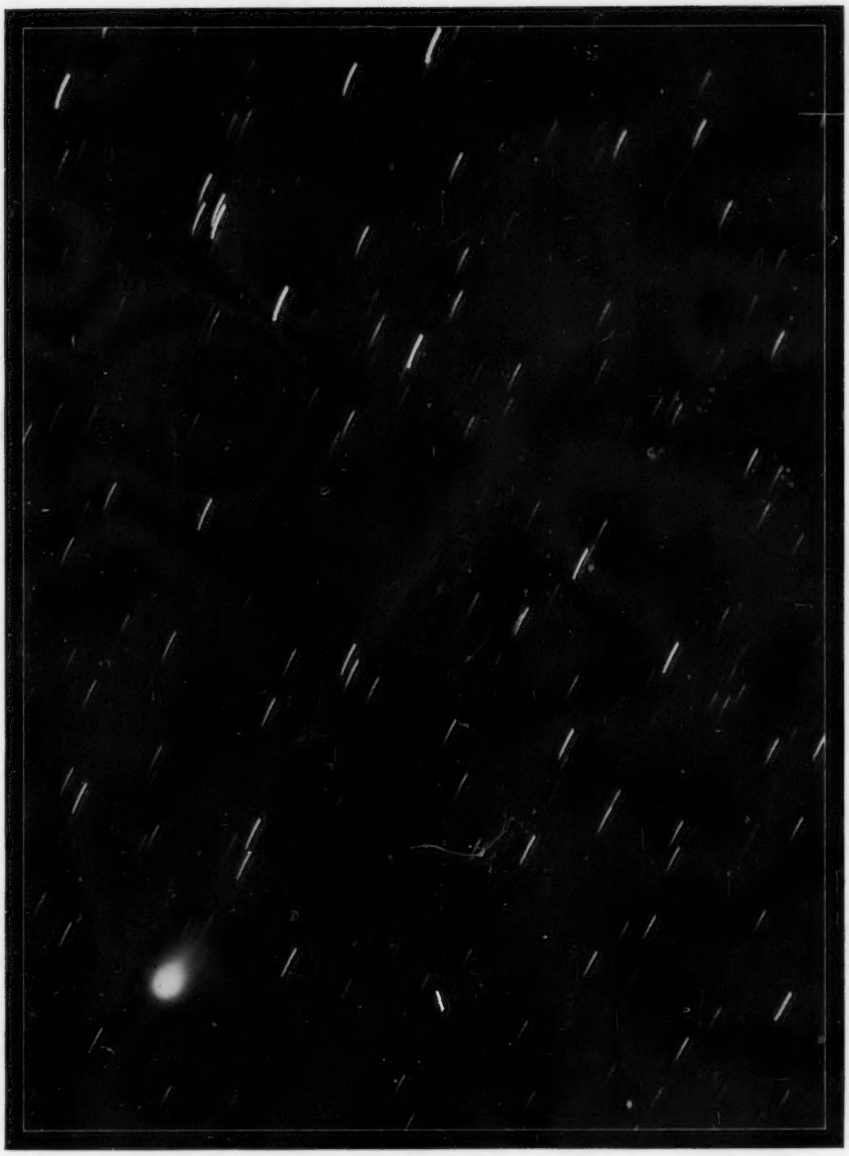
The plate of September 8 is introduced, not from any scientific value it may have, but from an artistic standpoint and from its unique character. So far as I know this is the only comet, or star photograph, on which clouds are actually shown. The exposure was very short, for the comet was visible for only a few minutes in a break. The clouds stand out black and distinct on the dawn-lit sky. To the eye it was a beautiful and striking scene—the comet in pale but clear relief on the dawn-whitening sky, the dark clouds, through a break in which the comet shone, and the solemn stillness of the morning, made it a picture not soon to be forgotten. The photograph rather faithfully records the appearance of the comet and clouds and dawn-lit sky, but the reproduction cannot do justice to the

[1] See *Astronomische Nachrichten*, nos. 2914, 2919, 2988 and 2998.

reality. Quite a number of stars appear upon the original which heighten the artistic effect, but they have disappeared in the reproduction.

The great delay in the appearance of this paper has been due entirely to the difficulty of getting good half-tone reproductions. (E. E. B.)

PLATE I
West



Comet 1907 *d* (Daniel) on July 11, 1907, at 13^h 58^m C.S.T.
Exposure 2^h 12^m. Scale: 1 inch = 46′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE II

West

Comet 1907 *d* (Daniel) on July 15, 1907, at $13^h\ 52^m$ C.S.T.
Exposure $2^h\ 20^m$. Scale: 1 inch = 32′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE III

West

Comet 1907 *d* (Daniel) on July 17, 1907, at 13^h 59^m C.S.T.
Exposure 2^h 10^m. Scale: 1 inch = 50′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE IV
West

Comet 1907 *d* (Daniel) on July 19, 1907, at 13^h 54^m C.S.T.
Exposure 2^h 18^m. Scale: 1 inch = 49′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE V
West

Comet 1907 *d* (Daniel) on July 29, 1907, at $14^h\ 41^m$ C.S.T.
Exposure $1^h\ 40^m$. Scale: 1 inch = 44′
10-inch Bruce Portrait Lens. Yerkes Observatory.

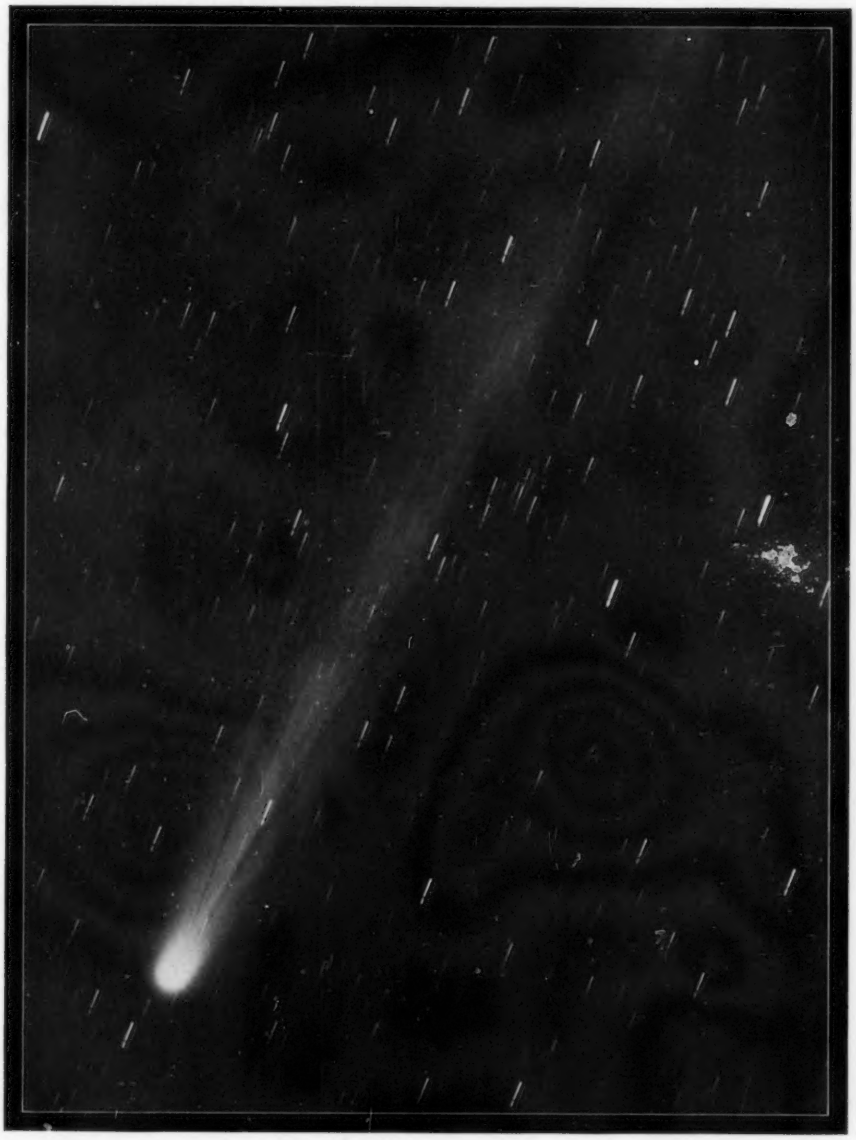
PLATE VI

West

Comet 1907 *d* (Daniel) on August 3, 1907, at $14^h\ 53^m$ C.S.T.
Exposure $1^h\ 40^m$. Scale: 1 inch = 49′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE VII

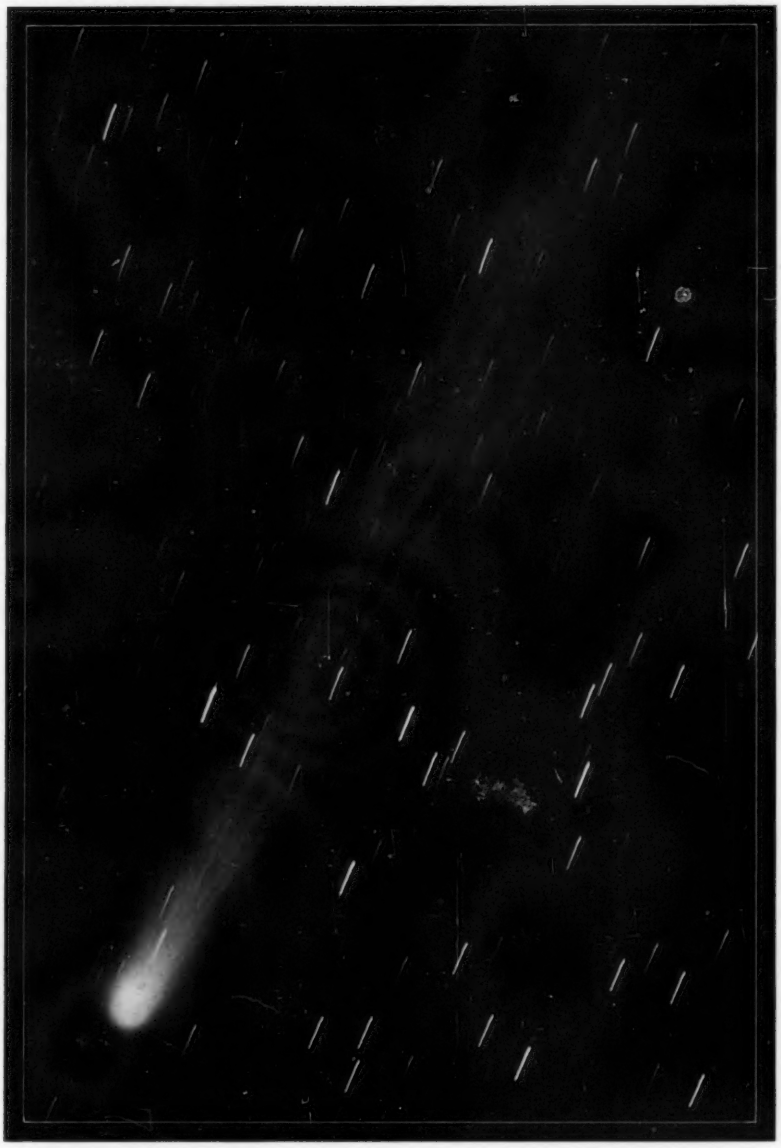
West



Comet 1907 *d* (Daniel) on August 5, 1907, at $15^h\ 8^m$ C.S.T.
Exposure $1^h\ 6^m$. Scale: 1 inch = 42′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE VIII

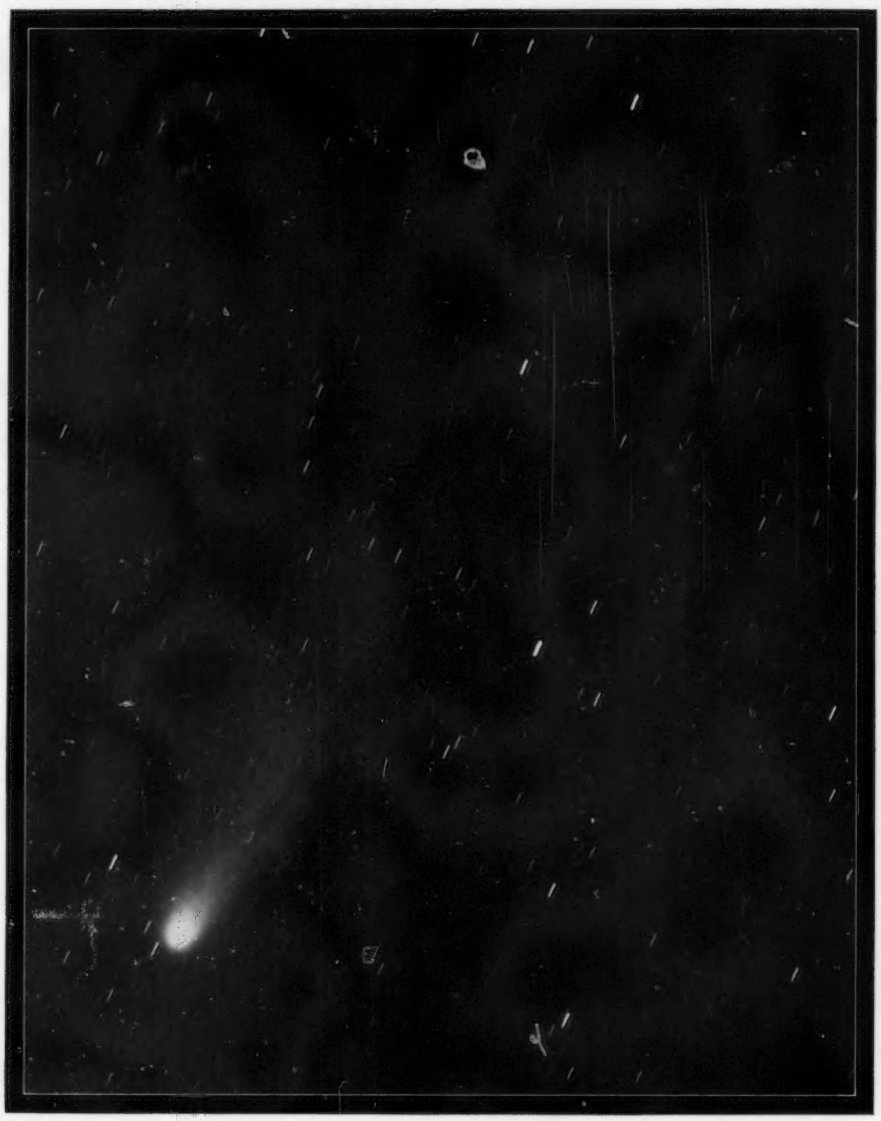
West



Comet 1907 *d* (Daniel) on August 6, 1907, at $15^h\ 3^m$ C.S.T.
Exposure $1^h\ 21^m$. Scale: 1 inch = 39′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE IX

West



Comet 1907 *d* (Daniel) on August 8, 1907, at 15^h 30^m C.S.T.
Exposure 0^h 33^m. Scale: 1 inch = 44′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE X

Comet 1907 *d* (Daniel) on August 9, 1907, at 15^h 1^m C.S.T.
Exposure 1^h 32^m. Scale: 1 inch = 50′
10-inch Bruce Portrait Lens. Yerkes Observatory.

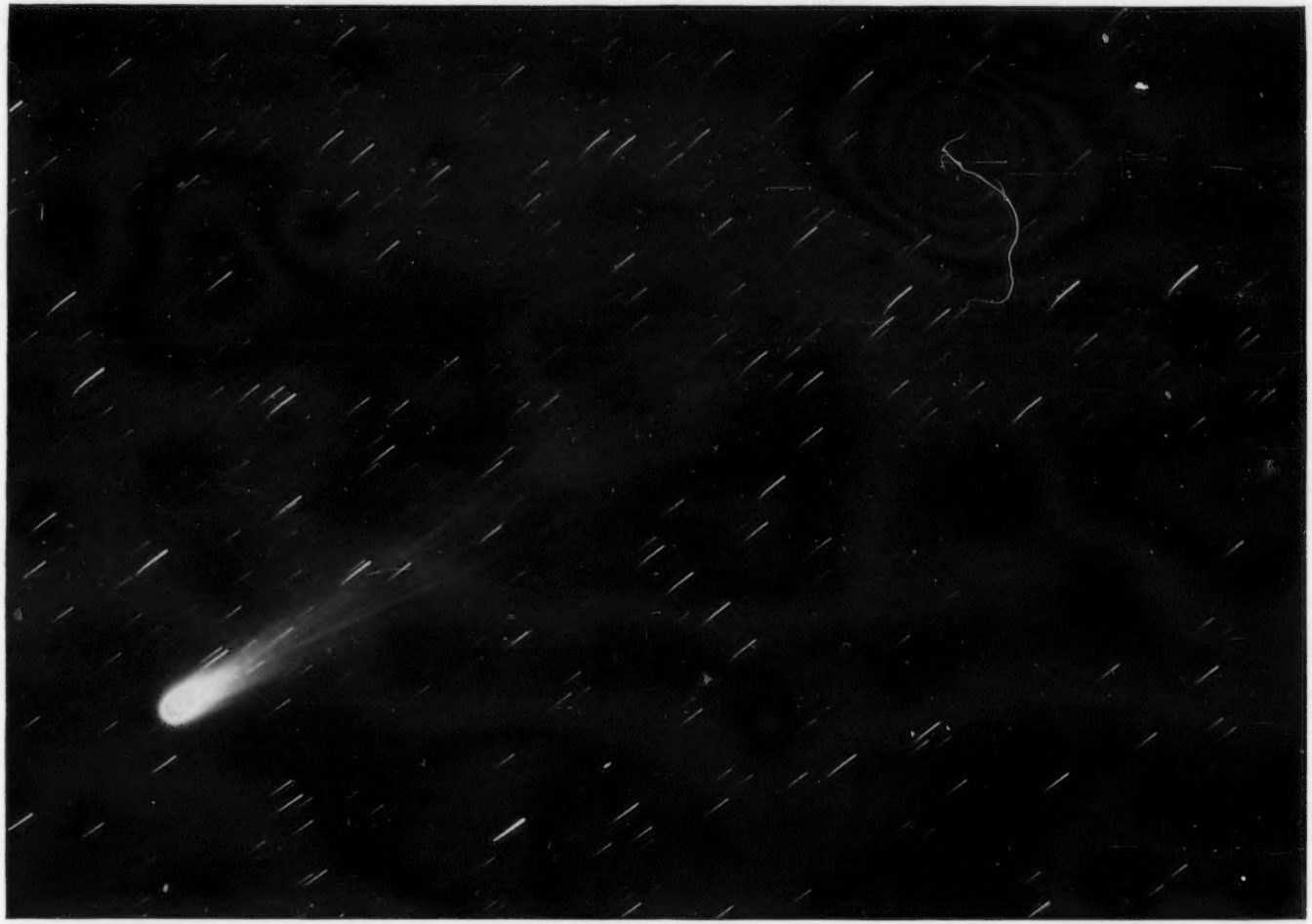
PLATE XI

West

Comet 1907 *d* (Daniel) on August 10, 1907, at 14^h 57^m C.S.T.
Exposure 1^h 43^m. Scale: 1 inch = 42′
10-inch Bruce Portrait Lens. Yerkes Observatory.

Plate XII

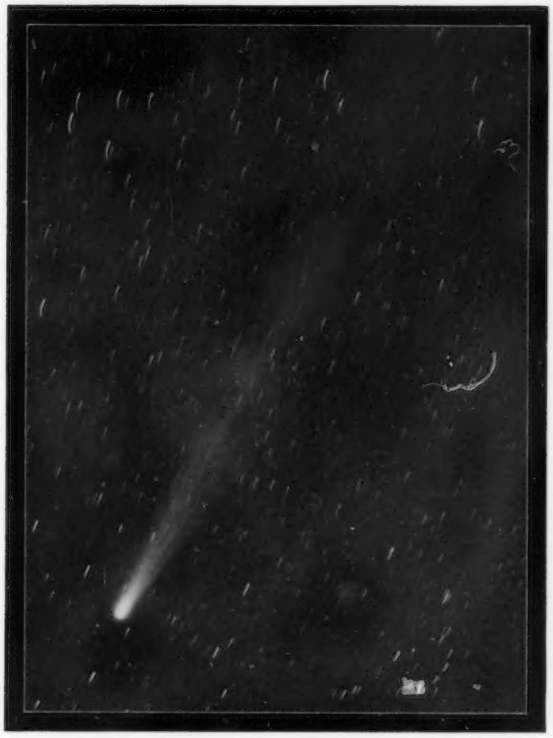
PLATE XII



Comet 1907 *d* (Daniel) on August 11, 1907, at 14^h 59^m C.S.T.
Exposure 1^h 42^m. Scale: 1 inch = 44′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XIII

West



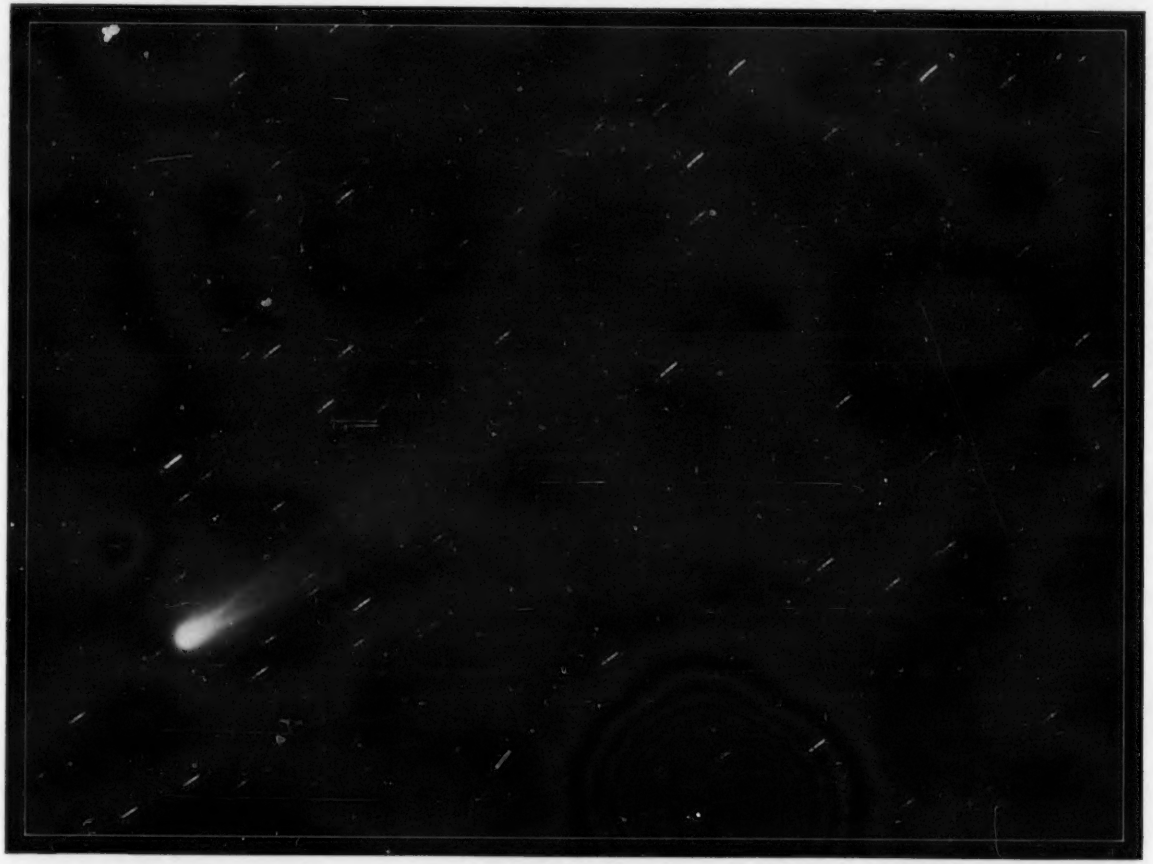
Comet 1907 *d* (Daniel) on August 11, 1907, at $14^h\ 59^m$ C.S.T.
Exposure $1^h\ 42^m$. Scale: 1 inch = 129′
3.4-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XIV

West

Comet 1907 *d* (Daniel) on August 12, 1907, at $15^h\ 7^m$ C.S.T.
Exposure $1^h\ 43^m$. Scale: 1 inch = 51′
10-inch Bruce Portrait Lens. Yerkes Observatory.

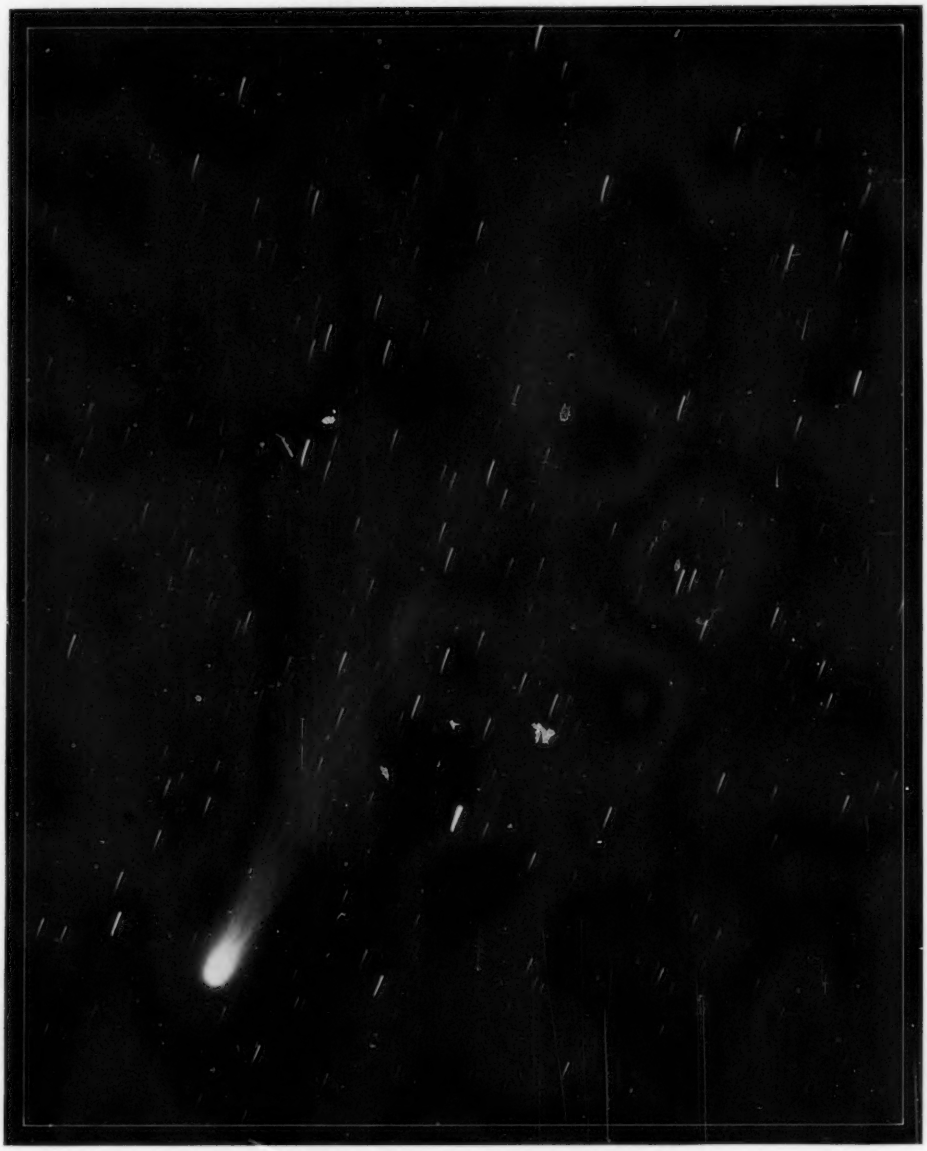
PLATE XV



Comet 1907 *d* (Daniel) on August 13, 1907, at 15^h 8^m C.S.T.
Exposure 1^h 11^m. Scale: 1 inch = 41′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XVI

West



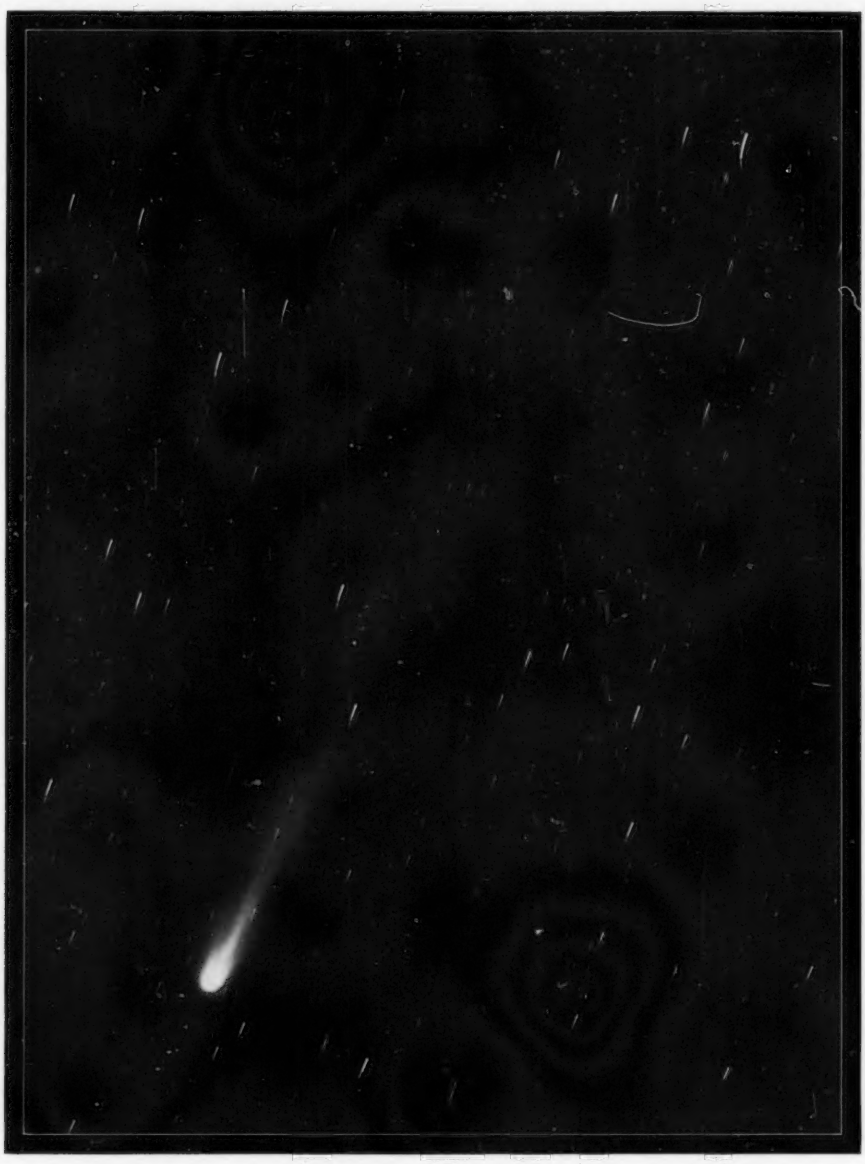
Comet 1907 *d* (Daniel) on August 14, 1907, at $15^h\ 11^m$ C.S.T.
Exposure $1^h\ 20^m$. Scale: 1 inch = 53′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XVII

West

Comet 1907 *d* (Daniel) on August 14, 1907, at $15^h\ 11^m$ C.S.T.
Exposure $1^h\ 20^m$. Scale: 1 inch = 14.1′
3.4-inch Bruce Portrait Lens. Yerkes Observatory.

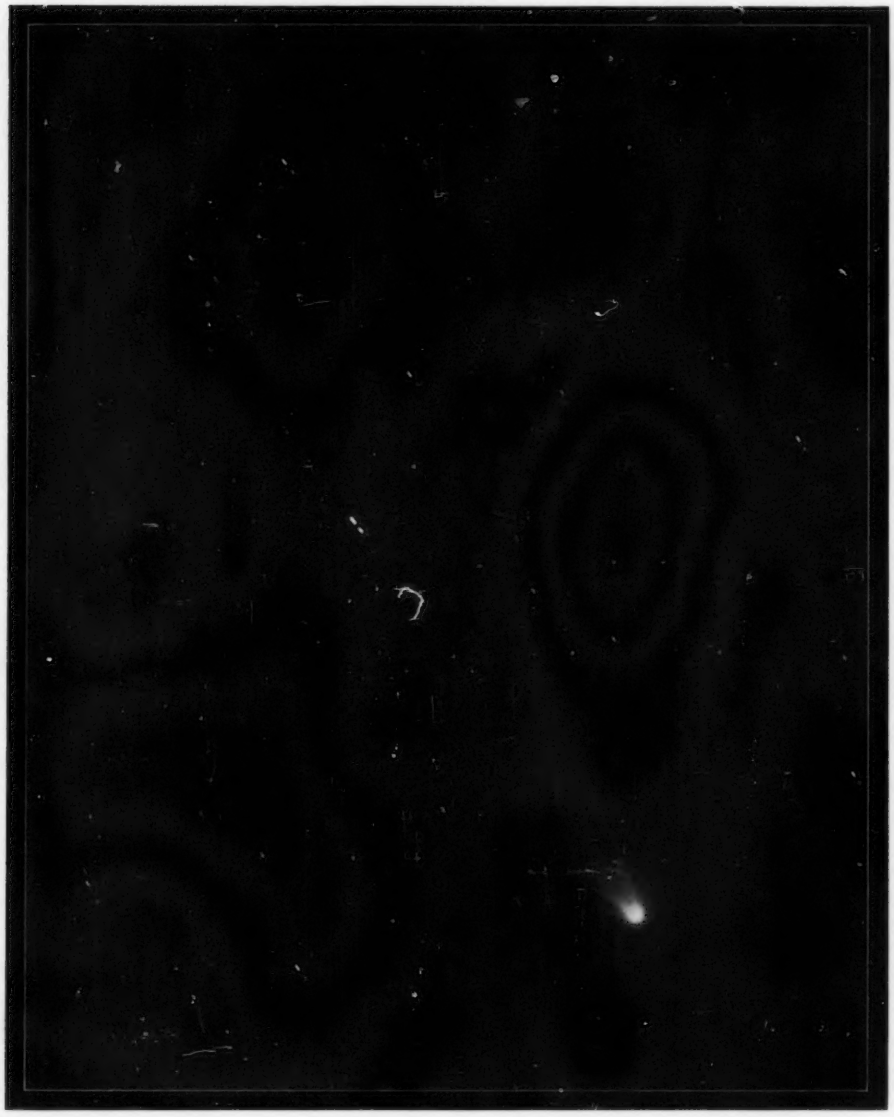
PLATE XVIII
West



Comet 1907 *d* (Daniel) on August 17, 1907, at 15^h 10^m C.S.T.
Exposure 1^h 30^m. Scale: 1 inch = 49′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XIX

West



Comet 1907 *d* (Daniel) on August 19, 1907, at $15^h\ 40^m$ C.S.T.
Exposure $0^h\ 40^m$. Scale: 1 inch = 36′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XX

West

Comet 1907 *d* (Daniel) on August 20, 1907, at $15^h\ 27^m$ C.S.T.
Exposure $1^h\ 5^m$. Scale: 1 inch = 53′
10-inch Bruce Portrait Lens. Yerkes Observatory.

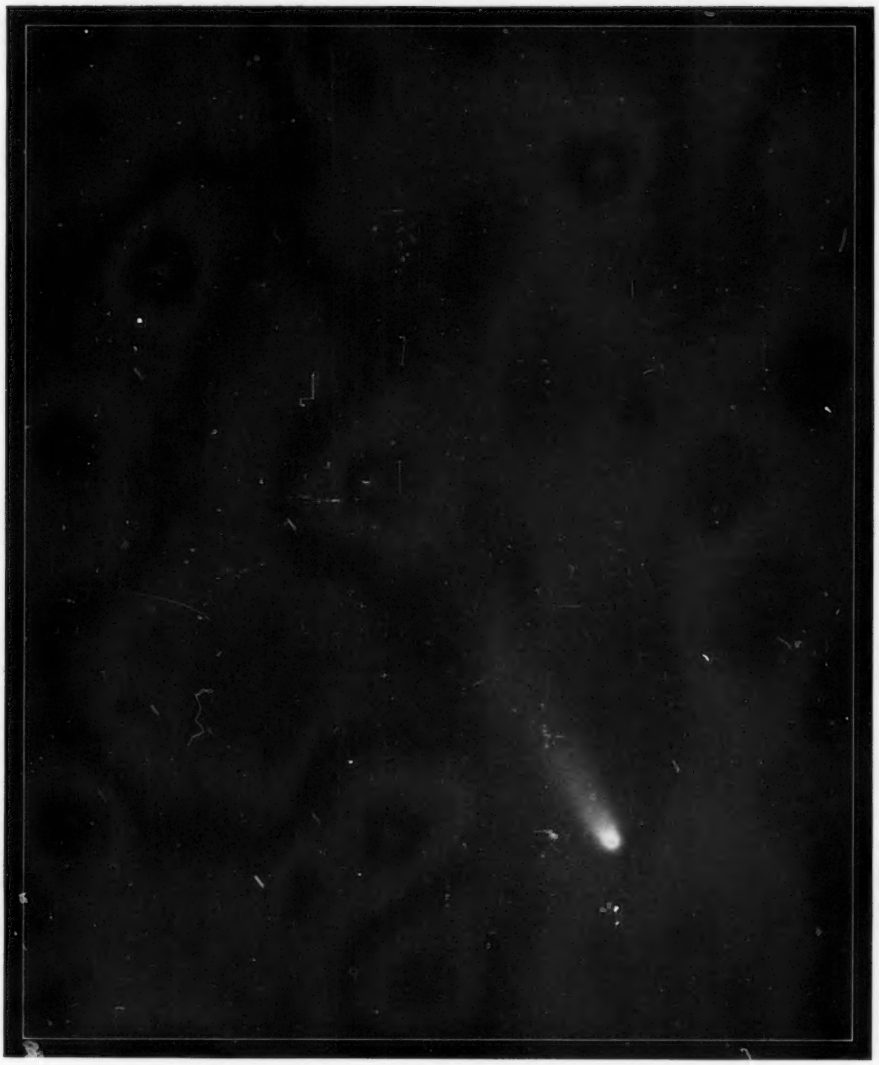
PLATE XXI

West

Comet 1907 *d* (Daniel) on August 21, 1907, at 15^h 36^m C.S.T.
Exposure 0^h 50^m. Scale: 1 inch = 56′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XXII

West



Comet 1907 *d* (Daniel) on August 24, 1907, at $15^h\ 48^m$ C.S.T.
Exposure $0^h\ 34^m$. Scale: 1 inch = 39′
10-inch Bruce Portrait Lens. Yerkes Observatory.

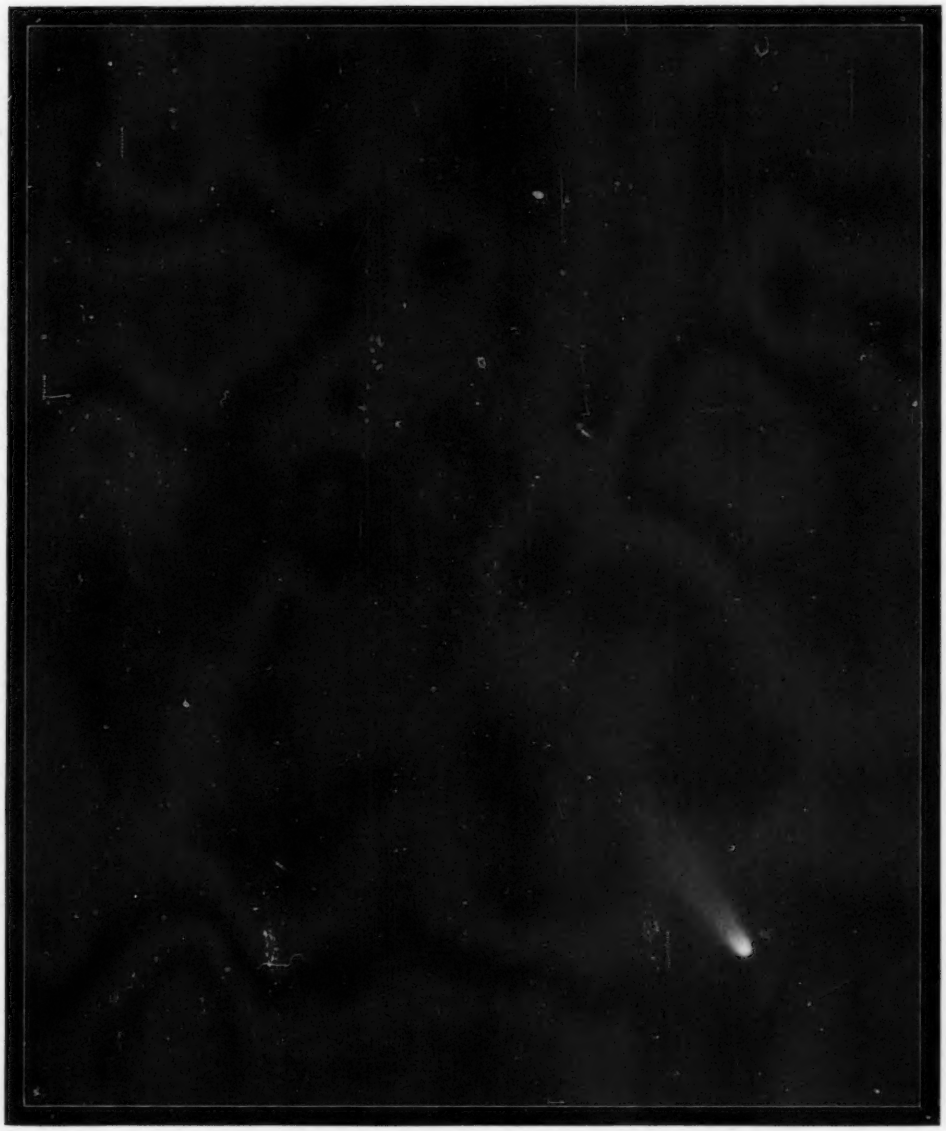
PLATE XXIII

West

Comet 1907 *d* (Daniel) on September 2, 1907, at 15^h 51^m C.S.T.
Exposure 0^h 18^m. Scale: 1 inch = 39′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XXIV

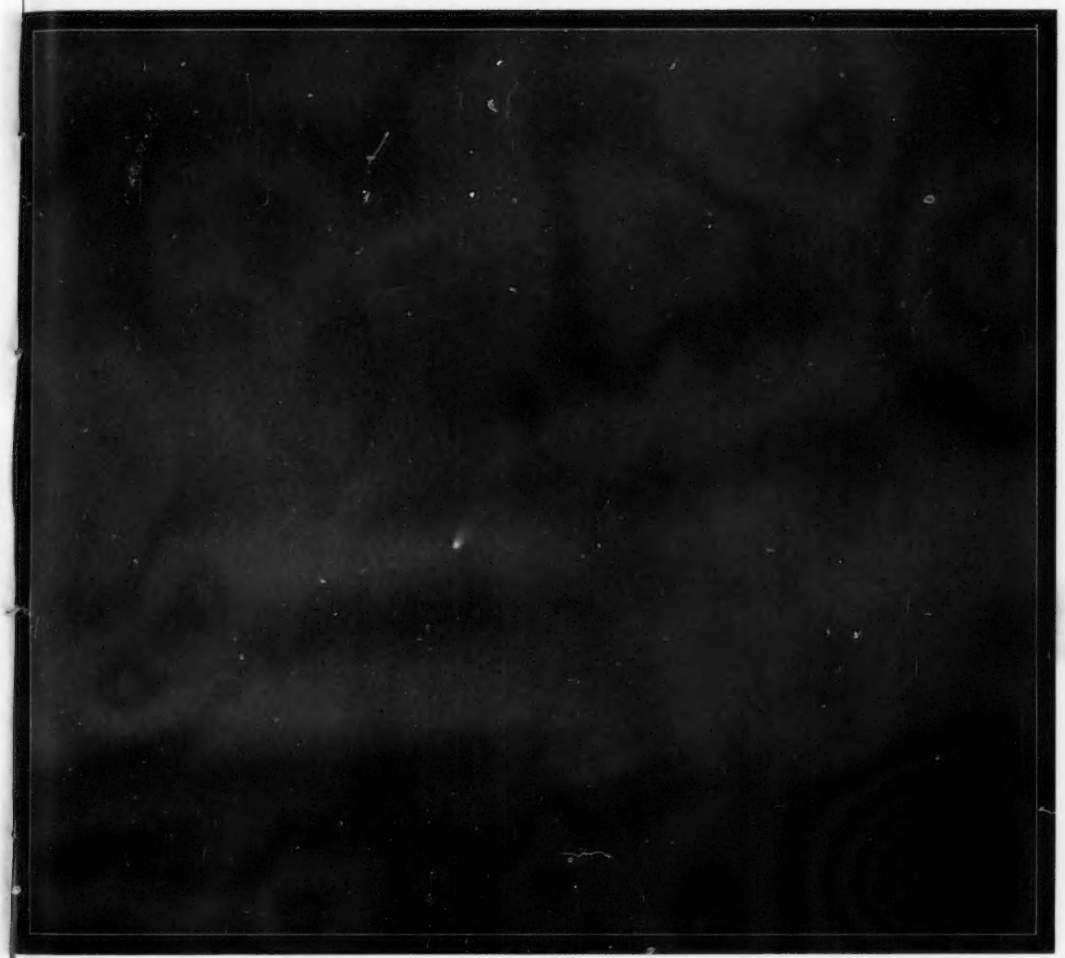
West



Comet 1907 *d* (Daniel) on September 5, 1907, at 16^h 0^m C.S.T.
Exposure 0^h 37^m. Scale: 1 inch = 38′
10-inch Bruce Portrait Lens. Yerkes Observatory.

PLATE XXV

West



Comet 1907 *d* (Daniel) on September 8, 1907, at 16^h 17^m C.S.T.
Exposure 0^h 5^m. Scale: 1 inch = 90′
6¼-inch Bruce Portrait Lens. Yerkes Observatory.

NOTES ON SOME PSEUDOMORPHS, PETRIFACTIONS AND ALTERATIONS.

By AUSTIN F. ROGERS,

Stanford University, Cal.

(*Read February 4, 1910.*)

The writer wishes to place on record some interesting cases of pseudomorphs, petrifactions and alterations observed by him in the last few years. Some of these are recorded for the first time, some are American occurrences of minerals known abroad, while others are good examples of commonly occurring pseudomorphs. While many examples of such pseudomorphs and alterations are of mineralogical interest only, some of them have a possible bearing on the origin of ores. My thanks are due to the gentlemen named in the several items who have kindly furnished me with the specimens which make this paper possible.

Pseudomorphs.

1. *Copper* after *Cuprite*.—Calumet-Arizona Mine, Bisbee, Arizona. Collected by Mr. E. W. Rice. Cubes of 4 mm. diameter, modified by faces of the octahedron and dodecahedron occur in cavities of a limonite gangue. The copper consists of dense aggregates of small imperfect crystals with smooth cube surfaces. No cuprite was observed in the specimen.

2. *Copper* after *Chalcanthite* (?)—Carlisle, Arizona. Collected by Mr. Harry Robertson. The specimen is a coarsely fibrous seam of native copper 2 cm. wide. There are no associated minerals to give a clue as to its origin and the mode of occurrence is unknown, but as copper is practically always a secondary mineral, and as the structure is exactly similar to well-known seams of chalcanthite from Arizona, it is believed to be a pseudomorph after chalcanthite.

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Pseudomorphs of copper after cuprite from Cornwall have been described by Miers;[1] copper after azurite from New Mexico by Yeates;[2] and copper after aragonite from Bolivia by Forbes.[3]

3. *Chalcedony* after *Calcite*.—Guanajuato, Mexico. Obtained from the Foote Mineral Company. An excellent specimen of this pseudomorph consists of pale brown chalcedony in the form of hollow doubly terminated scalenohedrons (2131) of calcite about 1 cm. in length.

4. *Hematite* after *Marcasite*.—Lake Co., California. Collected by Mr. H. E. Kramm from the Baker mine, six miles from Lower Lake on the road to Knoxville. The specimen consists of small encrusting crystals giving a red streak. They have the same form as unaltered marcasite crystals from the same mine.

5. *Limonite* after *Chalcopyrite*.—Granby, Missouri. Small tetrahedra (2 mm.) of dark brown limonite on a specimen of dolomite, calamine, and smithsonite have been produced by the alteration of chalcopyrite. The author found similar pseudomorphs at Galena, Kansas, but it is a rare kind of pseudomorph.

6. *Limonite* after *Cerussite*.—Burke, Idaho. Collected by Mr. H. F. Humphrey at the Bunker Hill mine. At this mine cerussite is a prominent gossan mineral. Several specimens show prismatic crystal aggregates of cerussite with a coating of limonite. Other specimens show limonite of a form exactly similar to the cerussite and are undoubtedly pseudomorphs.

7. *Wad* after *Calcite*.—Echo Mine near Mojave, California. Collected by Mr. H. W. Young. Cavities in a quartz matrix with the shape of calcite scalenohedrons are occupied by a soft black mineral answering the tests of wad. These are not direct substitution pseudomorphs but probably represent quartz encrustation pseudomorphs after calcite in which the calcite was dissolved out and then the cavities filled with wad.

8. *Calcite paramorph* after *Aragonite*.—Patterson Pass, east of Livermore, California. A travertine deposit in buff Miocene sandstone consists of a banded, coarsely fibrous aragonite of an amber

[1] *Min. Mag.*, Vol. II., p. 266, 1897.
[2] *Am. Jour. Sci.*, Vol. 38, p. 405, 1889.
[3] *Quar. Jour. Geol. Soc.*, Vol. 17, p. 45, 1861.

color, often variegated. The material has been quarried out in large blocks and on the exterior these are often altered to calcite. The aragonite is compact columnar massive, while the calcite is porous, though crystalline and shows the cleavage faintly. As the calcite retains to some extent the columnar structure of the aragonite the specimens are paramorphs. Occasional calcite crystals are found in cavities. Sicily furnishes excellent specimens of calcite paramorphs after aragonite, but this is the first example found in this country, I believe.

9. *Smithsonite* after *Calcite.*—Granby, Missouri. This is one of our best known pseudomorphs. Steep rhombohedrons of the —2R form ($02\bar{2}1$) implanted on dolomite have been replaced by a spongy mass of smithsonite, but the surfaces of the crystals are smooth.

10. *Smithsonite* after *Dolomite.*—Granby, Missouri. A massive cleavable dolomite specimen 2 cm. thick with warped rhombohedral crystals on one surface have been completely changed to smithsonite of a pale brown color.

11. *Cerussite* after *Calcite.*—Granby, Missouri. Scalenohedral ($21\bar{3}1$) calcite crystals of 1 cm. diameter are completely changed to colorless cerussite with adamantine luster.

12. *Pyromorphite* after *Galena.*—Granby, Missouri. Crystals of ½ cm. square cross section on chert matrix consist of a little unaltered galena in the center, then cerussite and finally a border of green earthy pyromorphite.

13. *Calamine* after *Calcite.*—Granby, Missouri. Scalenohedral ($21\bar{3}1$) calcite crystals 1 cm. in diameter on chert matrix have been replaced by calamine. When broken the crystals are found to be hollow and calamine crystals project into the hollow center.

14. *Muscovite* after *Tourmaline.*—Pala, California. A specimen 7 cm. long and 1.5 cm. in diameter represents an original tourmaline crystal, roughly trigonal in cross-section. It is now mostly white scaly muscovite in which is set a number of small black tourmaline crystals in parallel position with the large crystal.

15. *Talc* after *Actinolite.*—Apperson Creek, southeast of Sunol, Alameda County, California. Gray columnar, subradiating talc is

probably pseudomorphous after actinolite as it has the exact structure of the actinolite common in the schists of the Coast Ranges. The mineral has a greasy feel and is scratched by the finger nail. It is practically infusible and gives a little water in the closed tube. Cleavage flakes give a negative biaxial interference figure with a small axial angle. The axial plane is in the direction of the length of the columnar crystals.

16. *Chrysocolla* after *Cuprite.*—(*a*) Santa Margarita Mine, New Almaden, California (*b*) near Mammoth, Utah (Tintic district). At both of these localities chrysocolla is pseudomorphous after the chalcotrichite variety of cuprite, a variety that consists of crystal aggregates of elongated cubes crossing and branching at right angles. With polarized light, the chrysocolla exhibits an aggregate structure and the outside surface occasionally consists of concentric layers somewhat radiating. At New Almaden the cuprite occurs in seams in serpentine but it is believed to have its origin in copper-bearing pyrite which occurs in a nearby prospect shaft.

17. *Chrysocolla* after *Calcite.*—(*a*) Arlington, N. J. (*b*) Reward Gold Mine, Inyo County, California. Collected by Mr. C. E. Gilman.

(*a*) At Arlington chalcocite and secondary copper minerals occur at the contact between diabase and triassic sandstone. The pseudomorphs were found in cavities of the sandstone. They consist of small scalenohedrons ($21\bar{3}1$) completely replaced by chrysocolla.

(*b*) The Inyo County specimens are large prismatic quartz crystals coated with a crust of chrysocolla. Some of the chrysocolla is the form of acute rhombohedrons ($-2R$ or $02\bar{2}1$) with rounded edges which represents, no doubt, original calcite. The chrysocolla is made up of concentric layers, the inside ones of which are deeper greenish blue than the outside. Under the microscope the fine aggregate structure is in evidence. Associated cuprite is the source of the copper.

Petrifactions.

18. *Sphalerite* replacing *coral.*—Galena, Kansas. A conical coral, probably a *Zaphrentis,* 2 cm. in diameter, is replaced by dark granular sphalerite. Most of the fossils from the chert of this

district are molds or cavities from which the calcareous matter has been dissolved out. The specimen described is a cast probably formed by filling of the mold and not by direct replacement of the organism.

19. *Pyrite* replacing *Aviculopecten.*—Leavenworth, Kansas. Some excellent pyrite petrifactions were obtained from the Cherokee shales on coal mine dumps at this locality. The pyrite is bright brassy with purplish tarnish. The fossil is *Aviculopecten rectilaterarius,* which, in Kansas, is limited to this horizon.

20. *Limonite* replacing *gasteropod.*—Carnegie, Corral Hollow, California. Fossils of fresh-water gasteropods (probably a new species of *Melanea* according to Mr. Harold Hannibal) occur in Eocene sandstone exposed along the railroad track near Carnegie, San Joaquin County, California. The sandstone is composed of quartz grains with limonite cement. The shells are completely replaced by dense limonite .5 mm. thick.

21. *Limonite* replacing *twigs.*—Bingham, Utah. In Upper Bingham Canyon along the creek bed are found specimens of a porous mass of soft, earthy limonite. These evidently represent former plants as hollow, flattened stems are plainly visible.

22. *Malachite* replacing *cedar wood.*—Bingham, Utah. At the locality mentioned above, malachite with structure of the cedar wood common at the same place occurs. The mineral is porous and often has a mammillary surface in free spaces. The cell structure of the wood is visible with a hand lens. Selected pieces are completely soluble in hydrochloric acid showing complete replacement but in other cases there is simply a thin green coating of malachite.

23. *Barite* replacing *Productus.*—Elmont, Kansas. The writer is indebted to Dr. J. W. Beede for this specimen. A specimen of the brachiopod shell, *Productus punctatus,* has been completely replaced by pink barite and the surface markings characteristic of this species are preserved. A visit to the locality which is a limestone ledge two miles northwest of Elmont, Jackson County, Kansas, revealed a number of fossil pelecypods and gasteropods partially replaced by pink barite, but none so complete as the one described.

ALTERATIONS.

24. *Sulfur* from *Sphalerite*.—Galena, Kansas. Specimens of sphalerite and pyrite in chert breccia from the Templar ground, two miles southwest of Galena, Kan., show in an excellent manner the alteration of a sulfid to sulfur. The sphalerite is corroded and covered with pale yellow sulfur while the pyrite is fresh and free from sulfur. Evidently the sphalerite has furnished the sulfur.

25. *Strontianite* from *Celestite*.—Five miles from Austin, Texas, on the road between Mts. Barker and Bonnell. Collected by Mr. F. L. Hess. Massive cleavable celestite of a pale blue tint is much corroded and the cavities are occupied by tufts of small acicular crystals of strontianite. The crystals are flattened, tapering, six-sided crystals, the forms being a steep rhombic bipyramid (*hhl*) and a steep rhombic prism (*okl*). The crystals are often curved and in consequence give a wavy extinction. The elongation is parallel to the faster ray. The mineral contains some calcium in addition to strontium as the microchemical gypsum test shows. This is the best test for calcium in such a compound.

26. *Barite* from *Witherite*.—Northumberland, England. Colorless tabular barite crystals (*001, 110, 102*) are found in cavities of massive gray witherite. The barite is evidently a secondary product, formed from the witherite.

27. *Copiapite* from *Pyrite* and *Limonite* from *Copiapite*.—Five miles n. w. of San Jose, California. Altered pyrite crystals from chlorite-glaucophane schist boulders showed the following cross-section: The interior is hollow with small projecting bits of bright pyrite. The exterior is limonite while between these two is a soft compact yellow material which answers the blowpipe tests for copiapite. Under the microscope the copiapite is seen to consist of minute pseudo-hexagonal crystals. Here the pyrite has evidently altered to copiapite and then the latter to limonite.

28. *Hornblende* from *Hypersthene*.—Arroyo Bayo, twelve miles southwest of Livermore, California. These specimens were found in a large outcrop of norite or hypersthene gabbro. Grayish green hypersthene with faint cleavage has been altered around the borders to black hornblende with good cleavage. In fragments the hyper-

sthene has parallel extinction and characteristic pleochroism from pale reddish to greenish white while the hornblende has has an extinction angle[4] of about 14° and faint pleochroism from bluish green to yellowish green. The mineral occurs in large anhedra associated with light gray plagioclase.

29. *Sericite* from *Feldspars.*—New York City. Specimens of orthoclase and oligoclase from the pegmatites and pegmatite lenses of the schists in the upper part of New York City are often accompanied by secondary muscovite or sericite in the form of thin silvery scales. The scales occupy the cleavage planes but more especially planes of parting parallel to the unit prism faces (*110*).

[4] Determined on cleavage fragments.

MAGIC OBSERVANCES IN THE HINDU EPIC.

By E. WASHBURN HOPKINS.

(*Read April 21, 1910.*)

Various works in Hindu literature provide us with a storehouse of magical observances, from the time of Vedic Hymns onward. The Sūtras of one sort or another recognize and inculcate magical arts. But in epic literature, what is formally taught elsewhere is found in active operation. There is lacking, of course, any systematic treatment of these magical rites; they must be culled piecemeal from epic narration. Further, the relative importance of magical rites is lost, because to the heroes of the epic some magical observances were much more important than others. Finally, it must be said that at the time of the epic there was no sharp distinction felt between the regular sacrifice and the irregular magical sacrifice. All sacrifice was to win power, often from deities opposed to the sacrificer; but they were constrained to grant his wishes by the (magical) power of the rite. The same is true of the practice of austerities and ascetic observances, which, when persisted in, made the gods uneasy, because by means of such observances the ascetic won power over the gods themselves. Hence the religious devotion of a saint appalled the gods and they tempted him in various ways to fall from his asceticism, not because they disliked him or what he did, but merely as a means of self-defence.

On the other hand, magic *per se* was strictly divided into good and bad magic. The difference lay not in the rite itself so much as in the application of the rite. If one's adversary was a demon, who naturally employed magic, then a good man himself might use the same means. Injurious magic was justified against an injurer. All the gods as well as the demons use such magic and men may do as the gods do, but with the same restriction, that is, that their magic be Aryan or "noble," not for base purposes. Hence we are

told that when a king and his priest perform a magical ceremony involving murder they are sent to hell (see below).

A great deal of magical lore lies in the wonder stories of the holy watering-places called Tīrthas. We read that at such and such a Tīrtha the footprints of the gods are still visible, that "fishes of gold" are to be found, that animals change their shapes, etc. Primarily, the Tīrthas are in the interest of the accepted religious cult and the reward offered for a journey to a Tīrtha and a bath in the sacred pool is forgiveness of sins, 3.47.29, etc. But besides this the pilgrim gets "all his wishes" or more specifically "regains his youth," or gets "beauty and fortune," as in 3.82.43f., *ib.* 111f.; 85.32. That diseases are cured in the Tīrthas, 3.83.50f., may be due rather to a belief in medicinal waters and is not necessarily a magical trait. But it is a trifle more magical when we read that if one eats once at the Tīrtha called Maṇināga he will never thereafter be poisoned by snake-bites, 3.84.109f. In the same section it is said that the tracks of the magical cow Kapilā "and of her calf" are preserved till now at the Tīrtha named for her, *ib.* 88.

The Tīrtha is, in short, the place where marvels are to be seen, and these marvels are of more or less magical nature, like the "marvel visible even today at Piṇḍāraka" (in Gujarat), viz., "impressions having the mark of the lotus and lotuses stamped with (Śiva's) trident," 3.82.66.

Like the Tīrthas, the trees and mountains show many magical touches, but these require separate treatment.[1]

Magic in Sacrifice.

It must be assumed at the outset that all the paraphernalia of the Vedic cult, with its fire sacrifice, *havyam* and *kavyam*, 7.59.16, sacrificial sessions, "four-month" sacrifice, the "five sacrifices," 5.134.12 (cf. 19); the "six *sādyaskas*," the *sarvamedha*, the "seven *soma-saṁsthas*," 12.24.7; 29.38, etc., were perfectly well known to the writers of the epic. Thus the horse-sacrifice and human sacrifice are referred to, *e. g.*, 5.29.18, and the countless

[1] Compare my forthcoming paper on "Mythological Aspects of Woods and Mountains in the Hindu Epic," JAOS. 1910.

cattle sacrificed by the various kings who are extolled by the poets are the same as in earlier ages, only that the numbers (cf. *e. g.*, the *jārūthyas*, 3.291.70), like the gold employed, 7.61.6, etc., exceed all probability. These need not be described. Indeed the epic does not describe them. It merely mentions them, as it does the "divine and woodland rule" of performing *rājarṣiyajñas*, 3.240.16. Only in the case of the horse of victory and its subsequent sacrifice do we get a real picture of epic sacrifices of the old sort. It is rather the new features that are instructive, such as the actual presence, in sight of man, of the gods (at sacrifice), 7.67.19; the later insistence on make-believe sacrifices, seeds representing animals, etc., as in 12.338.4 due to the doctrine of non-injury, and the sacrifices not so orthodox as those just mentioned, which smack of magic, though even the regular sacrifices are performed as mere magical rites, by which, for example, India wins the lordship of gods, 12.20.11 (cf. 5.140.14, the girls' pots and plants in sympathetic magic).

One of the most interesting of these is the human sacrifice described in 3.127.2f.; 128.5. Jantu was the only son of Somaka and his father feared that he would die and leave him childless. He therefore exhorted his domestic chaplain to devise some means by which he might secure more sons. The sinful means devised was the sacrifice of Jantu. The various wives of the king stood about the cauldron where the wretched child was being cooked and sniffed the steam and smoke. This evil sacrifice had two results. The child was reborn as the eldest of a hundred sons conceived by the wives in this process of sniffing; but on the other hand the wicked priest had to go to hell.[2]

That a domestic priest has occult power over the king is generally admitted. He is able "to sacrifice the strength of the king"

[2] The artificial "sacrifice" of life (5.141.29f.) in battle is taken seriously by the epic poets. Compare 5.58.12 (to Yama): Śiva "sacrificed himself in the *sarvayajña*, and so became god of gods," 12.20.12. "In battle a warrior makes a sacrifice (as if making an oblation into fire, *hutvā*) of his body," 3.300.36; so 12.24.27, etc., Śibi sacrificed himself, in a pretty tale, by cutting off his limbs to save a fugitive; but the demon Rāvaṇa cut off his own heads and offered them in fire, which pleased Brahmā so that he let them grow again, 3.275.20.

or of the enemy, "on the sacrificial fire" *medhāgni*, that is, it is a magical fire-ceremony, 5.126.2; 9.41.12. In the horse-sacrifice, the head is cut off and set on the fire-altar, 7.143.71, that the chief part of the rivals may be destroyed. Even the demons fade away when the domestic priest of the gods "puts meat on the fire with a view to their abolition," 9.41.30.

The sacrifice of a hundred conquered and captured kings to Śiva (Rudra) intended by the victor, king Jarāsandha, calls forth the remark in 2.22.11 that "no one ever saw the slaughter of men"; but the entirely casual statement that "there is just as much merit in going to the holy well of Nandinī as there is in sacrificing human beings," 3.84.155, seems to show (since the speaker's object is merely to exploit this Tīrtha) that human sacrifice was regarded as something actual, and rarely beneficial. In 10.7.56 a man "sacrifices himself as an offering," and being accepted by the god comes out alive with divine power.

Many of the sacrifices made by the epic heroes, however, are simple offerings of "words, water, and fruit," 3.36.45; 41.47. Sacrifice is a means of purification: "By various sacrifices cleansing off the sin committed let us go to heaven" (*pāpam avadhūya*), 3.52.20. The usual sacrifices offered by those dwelling in the woods are *iṣṭi, pitṛyāṇi,* and *kriyās,* 3.25.3. A royal list may be illustrated by those offered by Yudhiṣṭhira, to wit, "*vāiśvadeva, iṣṭi, paśubandhu, kāmyanāimittika, pākayajña, aśvamedha, rājasūya,* and *gosavas,*" 3.30.14f.[3] There is also a *quasi* sacrifice of feeding a white bull till it can eat no more, by making offerings to it as to something sacred, *anaḍuhe sādhave sādhuvāhine . . . sāuhityadānāt* (to satiety), 3.35.34.

Only a king may offer a royal sacrifice, but there is another "just as good" (as efficacious) which an ambitious prince may offer. Its present interest lies in the fact that it is something quite new. "You cannot have the Rājasūya while the king lives," says the priest to the ambitious prince, "but there is another great sacrificial

[3] In 7.68.10, *ukthyas, aśvamedha, agniṣṭoma, atirātra, viśvajit vājapeya; ib.* 66.7, *darśapūrṇamāsāu, āgrayaṇa, cāturmāsyas,* etc. Compare also 7.63.1 f. which adds *puṇḍarīkas,* and remarks that the king gave "all the property of those not Brahmans to the Brahmanas."

session equal to the Rājasūya." Out of the gold collected as tribute is made a golden plough and with it is ploughed the earth for the altar, *yajñavāṭasya bhūmiḥ,* and a great ceremony called Vāiṣṇava, "very well prepared," *susaṁskṛta,* is performed, rivalling the Rājasūya. No one except Viṣṇu ever performed this sacrifice, and the priest says it seems to him even better than the Rājasūya: *etena ne'ṣṭavān kaścid ṛte Viṣṇum purātanam, rājasūyam kratuśreṣṭhaṁ spardhaty eṣa mahākratuḥ; asmākam rocate cāi 'va śreyaś ca tava,* etc., 3.255.13–21. This rite closes with scattering corn and anointing with sandal-paste; but "some said it was not equal to one sixteenth of the other" (the Rājasūya).[4]

Sacrifice.

"Sacrifice arose in the eastern country," says the epic, 5.108.5 and 9. This is more important as showing that the eastern country (district) was no longer as of old regarded as foreign.

Like other things, sacrifice is personified. The Great Father lives in the north with Sacrifice, 5.111.15. The Great Father, by the way, brings a sacrifice, as much as do the other gods, *iṣṭīkṛtam nāma (satraṁ varṣasahasrikam),* 3.129.1.

"A sacrifice without gifts (to the priest) is dead," is another saying of the epic, *mṛto yajñas tv adakṣiṇaḥ,* 3.313.84. Cf. 5.106.22, etc.

The merit of a sacrifice pertains to the giver; but he may give that merit away to another, 5.122.13, etc.

Most of the gods sacrifice as they accept sacrifice. They are "perfectors of the sacrifice," *sviṣṭakṛtaḥ,* 5.42.40 (rare epithet of gods in general; usually of the Fire-god alone). The gods are established through sacrifices, and sacrifices are produced through

[4] This is a standing expression of depreciation, as in 3.34.22; 39.23; 174.3; 254.27; (above) 257.4; 4.39.14; 5.49.34; 7.36.7; 111.30 (31, *nā'lam Pārthasya!*); 7.197.17; 8.15.28. Compare 12.174.46 = 177.51 = 277.6. The fraction is scarcely used otherwise save in the late geographical section of Bhīṣma, where it is said that Kubera gives to man only one sixteenth of the quarter of Meru's wealth, which (quarter) he in turn receives (from Śiva), 6.6.23. In 10.12.17, "one hundredth part" and in 12.155.6, "one eighteenth part" are used in the same way as one sixteenth. But "one and one-half times" (better) is found in 7.72.34 and 11.20.1.

the Vedas, 3.150.28. Gods who "steal the sacrifice" are begotten by Tapas, and are fifteen in number (3×5), one group having Mitra-names, 3.220.10f. (Subhīma, Atibhīma, Bhīma, Bhīmabala, Abala; Sumitra, Mitravat, °jña, °vardhana, °dharman; Surapravīra, Vīra, Sureśa, Suvarcas, Surahantar).[5] A peculiar way of dotting earth with sacrifices is often alluded to in the epic. It is by casting a Śamī stick as far as it will go, and building an altar where it falls, over and over again, *śamyākṣepeṇa* (*ayajat*), 3.90.5, etc.

The general distinction made by the epic between the worship of gods and Manes is that the gods are honored with flowers and water and the Manes with roots and fruits, the former being *arcitāḥ*, revered, and the latter being *tarpitāḥ*, pleased, 3.156.6. Every sacrifice is identified with Prajāpati, as food, and the year, 3.200.38.

But besides the regular sacrifices and the substitutions for them[6] there is evidence (cf. 8.40.33, the Mantra of the Atharva to offset scorpion poison) that the use of the "Atharva Veda crammed full of wizardry" was familiar enough. The application of the art of magic was according to circumstances. Against one who used bad magic the use of bad magic was permissible; otherwise not. The difference between good and bad ("straight and crooked") magic was recognized and practiced both in the use of legitimate and illegitimate sacrifices and in the application of magic weapons and the like (magic clouds of dust, showers of blood, frightful shapes and noises) to defeat a foe. The Mantra sufficiently potent converted the ordinary weapon into a magical dart, a boomerang or thunderbolt, with which a good and true Aryan might fight the powers of darkness and any sinful knights who relied on such powers. Ethically, the rule was "magic is sinful; but if employed against the good the good may in turn use it." The same rule, in short, as obtained in the matter of curses. If cursed not it was sinful to curse; if cursed, it was silly not to curse back and the worse the curse the better the curser. Cf. 12.100.5; 103.27f.

[5] Foreign influence may be suspected in the Mitra-named "sacrifice-stealers." The others are native devils, to whom one offers sacrifice "outside the altar." The idea is Vedic. The last name in the text is paraphrased, *surāṇāmapi hantāram*, "*slayer of gods.*" Sureśa (Agni) is a proper enough name of a (good) god!

[6] Compare also *ātharvaṇa arivināśana*, "foe-slaying," 8.90.4; *Kṛtyā atharvāṅgirasī 'vogrā*, "like an Atharvan rite, horrible," 8.91.48; 9.17.44.

The use of charmed weapons was facilitated by a special ceremony called Lohābhisāra. Thus in 5.160.92, *lohābhisāro nirvṛttaḥ* means "That ceremony has been performed (for you) which forces the deities named by the Mantras you have used to preside over and govern your ordinary weapons." So all the deities of water, fire, etc., have their names given to the weapons thus inspired, and when a warrior is said to use the *Vāruṇa astra* it is merely an arrow inspired by the god named, who is temporarily at the disposal of the knight. This is a perfect parallel to the "singing of a weapon" on the part of an Australian savage and the Mantra is felt as nothing more than a magic formula. It is equally efficacious when said over a blade of grass, 10.13.19f. In 8.40.7, an arrow is "preserved for years in sandal-dust and religiously worshipped," *pūjitaḥ*, that it may be effective when needed.[1]

When Arjuna makes a lake spring up where there was no water, on the field of battle, he performs a similar magic trick, 7.99.62f., for it is done by piercing the earth with a magic arrow.

It must be observed that all these practices are in good repute if not exercised for a sinful purpose. The priest who knows magic is the king's domestic chaplain. The king himself is a magical being when as in the case of king Śāntanu he has the "healing touch," 1.95.46; "Whomsoever he touches with his hands, if worn out he becomes vigorous again." Certain priests are Brahmans of high character and yet have the honorary distinction of being *vidyājambhakavārtikāḥ*, that is, "conversant with wizardry and magic" (cf. *ib. jambha-sādhakāḥ*), 5.64.16,20.

The ordinary means of resisting disease was threefold, drugs, Mantras (holy verses), and "ceremonies," *kriyās*, as is succinctly expressed in the simile, "Karṇa attacked Yuddiṣṭhira like a fearful disease which has passed Mantras, drugs, and *kriyās*," 8.49.8. The *kriyā* is often identical with *māyā* (magic, illusion). In 9.24.54f.,

[1] The weapon is treated like an idol. One such magic weapon is a dart made by the great Artificer (Tvaṣṭar). It is kept for years and worshipped, "with perfumes, garlands, a seat, drink and food"! 9.17.44. Two magical weapons are described in 8.53.24f. One of them encircles the foes' legs with snakes and the other invokes birds of prey which eat the snakes (*pādabandha* or *nāga*, and *sāuparṇa*). When one's fated day arrives, however, the magical weapon refuses to act, 7.191.8.

the hero solidifies a lake and lies within it hidden from his foes. This is *māyā* but also *dāivayoga*, "divine power," *ib.* 30.56. The opposing hero is then exhorted to kill the fugitive by *māyā*, because "one who uses magic should be slain by magic," 9.31.7. The divine adviser, Kṛṣṇa, then says "for by means of *kriyā* (*i. e.*, magical ceremony) the demons were killed by the gods. Thus Indra slew Bali (etc.). This fellow here has used his divine *māyā* to hide in the water (31.4) and so you should kill him by *kriyā*-means, just as Indra slew Vṛtra, and Rāma slew Rāvaṇa, and I myself of old slew the two ancient demons Tāraka and Vipracitti. So other demons were slain by *kriyā* and it is by *kriyā* that Indra enjoys heaven" (31.14). Here the "ceremony" *kriyā* is synonymous with *māyā*, illustive magic, even deceit, as clearly in 5.35.42 where it is said that the use of Atharva Veda formulas, *chandāṅsi*, "do not save one who uses *māyā*, but desert him," as a sinner, parallel to one who drinks, quarrels, etc. Compare also 9.58.5f., where *māyā* is deception.

Hair.

The idea that strength resides in the hair may be indicated by the ascription of very long thick hair to ogres (Rakṣasas). These creatures have hair as thick and long as an elephant's trunk and a *trijaṭā* female, that is a female ogre with her hair in three braids, is especially fearful. Śiva himself bears the epithet Trijaṭa. On the other hand, the sign of defeat in battle is that one stands *patitamūrdhaja*, "his head-growth fallen," that is, with loosened hair, as in 3.280.66.[8] Suppliants have "loose hair," 10.8.107, and ghosts are bald, *ib.* 71. The hair of the Yogi droops, 12.46.5, as his intelligence wanes.

The type of weakness, the eunuch, had his hair done up in a braid, *veṇīkṛtaśiras*, 4.2.27; that is, like a woman. The one braid was also a sign of mourning. In R.2.108.8, "The city wears but one braid" means that the whole city mourns. Dishevelled hair

[8] The likeness to an elephant's trunk is made to show strength. On the contrary, Sītā's, the heroine's, hair is "like a black snake," being done up in a long braid (*kālī vyālīva mūrdhani*) *dīrghaveṇī*, 3.281.25f. Hair-dressing *keśakarma*, was the occupation of a Sāirandhri, 4.3.18 (*jāti*), a special caste.

also indicates mourning (compare the funeral procession, when all the mourners go *pracṛttaśikhāḥ*, "with loosened braids," AGS.4.2.9), that is, by analogy with the one-braid sign, weakness. It makes no difference for what one mourns, whether for the death of a loved relative, or the loss of a kingdom, or, it may be, for the loss of dignity. Thus in 5.40.15: "Men bring from the house the dead son and cast him on the pyre ('fire-heap') like a log, and weep with loosened hair; while another enjoys his wealth, and birds and fire enjoy the constituents of his body." But also, in mourning for the kingdom they have gambled away: "The prince went on, covering his face with his garment, and one brother threw dust upon his limbs and another greased his face, and the women wept with dishevelled hair and covered their faces with their hair," although the explanation given is that they did this in order not to be recognized; 2.80.4f. But, though this may be true of the grease and dust, in regard to the hair it is artificial, as may be seen from other accounts. Thus in 3.173.62f.: (when their men have been killed) "The women rushed out of the town with dishevelled hair, in excitement, distressed, like ospreys;[9] and with dishevelled hair they fell on the ground, mourning for their sons, fathers, and brothers; weeping and wailing and beating their breasts; devoid of wreath and ornament." Again, at 4.16.46, the insulted heroine "loosens her hair," or, in the fuller description of the South Indian recension, 4.20.59 and 77: "She bathes not, she eats not, she wipes not off the dust. . . . All her limbs are covered with dust like those of a female elephant . . . and she has her hair loose"; and she does not braid her hair again till the insult is avenged after twelve years, *keśapāśasya padavīm gato'si*, 12.16.28.

As a sign of disgrace, a conquered foe has to proclaim in public, "I am the slave of the Paṇḍus," and wear his hair like an ascetic in five little tufts. His conqueror "with his crescent-shaped knife made five tufts." He is then *pañca-śikha-* (SI. *pañca-saṭa-*) *kṛtaḥ*, 3.272.9 and 18. In 7.202.58 this designates Śiva (as ascetic).

[9] So in 9.29.68f. "the women beat their heads with their nails and hands, wailing like ospreys, and tore their hair and beat their breasts, shrieking 'alas, alas!'" "Covering the face with her garment" (in mourning) occurs in 9.63.68.

To be bald is to be disgraced anyway, and only hermits (*parivrajanti dānārthaṁ muṇḍāḥ kāṣāyvāsasaḥ*, 12.18.32) and barbarians shave their heads. The hermit is *muṇḍa* or *vikaca*, "shaved on the head," 3.260.12 (of a Śivaite ascetic), and the poet, in describing the heads of the barbarians on the battle field, says that they had "beards but no hair on their heads," which made them look like cocoanuts. Probably ethnic characteristics lie back of the "tufted hair" of Buddha and the standing epithets applied to Kṛṣṇa and to his chief disciple, Arjuna, who are called, respectively, Hṛṣīkeśa and Guḍākeśa, *e. g.*, at the beginning of the Bhagavad Gītā 6.25.24. The obvious etymology would make the first "stiff-haired" and the second "ball-haired" (cf. *hṛṣita*, of hair standing on end; but native piety divides the word into *hṛṣīka-īśa*, "lord of senses"). Hair with curly ends is praised. Kṛṣṇā, the heroine of the great epic, has blue-black hair with its own perfume and glow like that of a snake, "with twisted (curly) ends," *vṛjināgrā*, 5.82.33.[10]

The squaws of some of our American Indians were accustomed to make a hair-parting through the middle of the crown and daub it with red paint, presumably to keep evil spirits out, as they used red paint for that purpose very generally. The same practice obtained in epic times (as it does today) among the ladies of India, though, like the squaws, they regarded it as merely ornamental to decorate themselves thus.[11]

The casting of hair into the fire exhibits all the trait of a magical ceremony. In 3.136.9f., Rāibhya, a saint, cast into the fire two locks of his hair, and out of the fire came a woman and a male ogre, "with horrible eyes and terrible to see." This male ogre then pursued the enemy of the saint; who could not escape

[10] The signs of excellence in horses include (at 3.71.14) ten twists or curls called āvartas, which show good qualities. Compare Caland, *Over het Bijgeloof der Haarvervels op het paard*. In man, *tūbaraka* (hornless) "beardless" is equivalent to eunuch. "Bhīma would kill anyone who should say to him 'O thou *tūbaraka*'," 8.69.73. "Curly red hair" characterizes the foreign van-guard of a model army, 12.101.16.

[11] Catlin says that no one knows why the Indians so decorate themselves, and he himself cannot think of any reason.

The middle parting was customary: *susaṁyataṡ cā 'pi jaṭā vibhatkā, dvāidhīkṛtā bhāti lalāṭadeśe*, SI.3.113.9 (*viṣaktā. . nātisamā lalāṭe*, B.112.9).

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into water, as the water dried up at his approach because he had become impure—another magical touch.[12]

Among the baths and sacred watering-places, there is one which goes by the name of Śvāvil-lomāpanayana in the Bombay text and Śvāna-lomāpanayana in the South Indian recension, at 3.83.63 (also *-lomāpaha*). This should mean the "removal of hair of porcupine" (or "of dog"), and the place probably commemorates some legend now lost; but the remark added to the name is "there (nowadays) priests pluck out their hair," and "being thus purified attain the blessed state." This is preceded by the mention of another watering-place, apparently near by (perhaps a rival Kurhaus), which "purifies merely by going to it; and one becomes purified (from sin) by drenching his hair in it" (the holy water). B. calls this Sītavana and the SI. text again differs slightly in making the name Śītavana. This last too is the reading in C. and it is probably correct as it has meaning ("the cool grove"), whereas the Bombay text is either meaningless or a corruption of "Sītā's grove," which is unlikely. In the description of the act leading to purification, *keśān abhyukṣya vāi tasmin pūto bhavati,* the "drenching of the hair of the head in this (water)" may imply casting the hair into the water, but that is not certain; while at the other watering-place the hair is certainly plucked out and (inferentially) sacrificed in the water.[13] No religious force lies in "arrange thy hair" (in preparation for battle) in 9.32.60.

The Evil Eye.

The "eye of wisdom," 3.209.50, etc., is a mental power. It is with a glance of the eye that Sagara's sons are burned by Kapila,

[12] It is curious that this hair-born ogre does not disappear or perish when he has completed the task for which he has been created. On the contrary, he gets as his reward the woman created from the other lock of hair. Her part in the matter was to make the man impure through tempting him, which she easily did as she was very fair and he was not very virtuous.

[13] Naturally, "grasping by the hair" is insulting (M. 4.83) and when the heroine of the epic is basely treated this only adds to the insult. There may, however, be a relic of superstition in it. At least Droṇa's son feels more distress at the fact that his father's foe "seized him by the hair" than on any other point in his manner of death, 7.195.8f., *keśagraha(ṇa)*. Proverbially "up to hair-seizing" means to the limit, as in R.3.46.2 ("I must strive") "as hard as I can," to the last.

according to one version of the story, as they were digging out ocean on earth's surface.[14]

That serpents have poison in their look may be inferred even from the common word for such poisonous reptiles, *āśīviṣa,* the black "poison-tooth" cobra, as compared with its synonym (*dṛgviṣa*), *dṛṣṭiviṣa* or *dṛṣṭīviṣa,* "poison glance," which, be it observed, is applied indifferently to snakes and to human beings (another word meaning "eye-poison," *netraviṣa* is used of the *āśīviṣa* serpent only, as "possessed of poison from the eye").

Many incidental remarks testify to the belief that a look may injure. Rāma's "mere look" killed the dragon-worm, 12.3.14. In 3.138.13, it is said; "Let not the one who slays a priest see thy sacrifice; by even a glance he could injure thee," *brahmahā prekṣitēnā 'pi pīḍayet tvām.* The inference here, that the evil eye is associated with an evil nature, is obvious; yet it does not follow that the injury to be done is voluntary. On the contrary the idea of envy, invidia, being at the root of the evil eye is probably not the primitive idea but a secondary notion. The evil eye works without its owner's will, though the will to cast the evil eye may on any occasion be present: "Beware lest the eyes of the weak consume thee" (they are compared with the eyes of a snake and a saint in power), 12.91.14f. Yet the action may be as effective without the wish to injure, and this is why the wedding-ceremony from the beginning associates *aghoracaksur apatighnī,* "(be) a wife without the evil eye, not a husband-slayer."

This word *ghora* is indeed in the epic associated with the "look of poison." In 5.16.26 it is said: "Never look thou upon Nahuṣa, who takes away energy; who has the poison-look; who is very terrible, *tejoharaṁ dṛṣṭiviṣaṁ sughoram.* In a following verse: "Let us overcome Nahuṣa who has the terrible glance, *ghoradṛṣṭim,* our enemy," 5.16.32. The two verses show that *dṛṣṭiviṣa* and *ghoradṛṣṭi* are practically synonymous.[15]

[14] 3.47.9–19, *darśanād eva.* The account in 3.204.27 says that they were destroyed by fire which came from the mouth of Kapila.

[15] The meter of the last verse is noticeable, *Ripum jayāma tam Nahuṣam ghoradṛṣṭim.* It should be added to the list given in my Great Epic, p. 299; also 5.29.16c: *tathā nakṣatrāṇi karmaṇā'mutra bhānti,* and the verse (not in B) C.797, *asatyām āpadi karmaṇi vartamānaḥ.*

Nahuṣa himself says of his power: "Whatever living creature I look at with my eye, his energy I quickly take away; that is the power of my sight," *dṛṣṭer balam mama*, 3.181.35. There is no implication that he wishes to do ill. The queen's eye made a sore on her nephew's finger; but with her look she might have consumed him, 9.63.65; 11.15.30.

The expression used in 3.151.6, "fruitful has my eye become," that is my sight has been blessed (through seeing thee), *mamā 'pi saphalam cakṣuḥ*, is due rather to picturesque language than to any peculiar view of the eye.

Minor Magical Traits.

The reverence accorded to the *catuṣpathas* or places where two roads meet, making "four paths," is probably due to the belief that evil spirits haunt such places, 6.192.58. To enter a place "Not by the door" is consonant only with evil designs, 2.21.53; 10.8.10.

Another relic of superstition due to magic is the aversion to leaping over another person. The feeling is so strong with savages that in some parts of the world houses are not built with two stories because of the avowed objection to the presence of another human person above the lower inmate of the dwelling. But in the epic the idea of the world-soul has blotted out this older view and the reason given for not leaping over another is explained by this later belief. Thus Bhīma refuses to vault over his brother Hanūmat, saying: "If I did not know that Being who has been manifested in all beings through tradition, *āgama*, I should vault thee, as Hanūmat did the sea; but as it is, I will not insult the Supreme Being (in thee) and will not leap over thee," 3.147.8f.

Conception by sniffing or inhaling sacred fumes, of sacrifice, etc., is sometimes varied by smelling or tasting a brew prepared with Mantras (holy formulas), and sometimes combined with tree-marriages (q. v.). But a more purely magical touch is furnished by the ceremony alluded to in 4.3.12: "I know the bulls having good signs, by smelling the urine of which even a barren woman conceives." Water alone may be doctored by a priest so as to have the same effect, 3.126.20. A god revives the dead with a

handful of water, 12.153.113 (SI.v.l.); though one may also be revived by divine fiat, or by a magical plant, 10.16.16.

Water-magic is inherent in a good many observances of the epic. Water dries up before a sinner, as in the case of the wicked priest who ran away and tried to escape through water, 3.136.9f. Water is a divine witness of wrong, 1.74.30. It is probably for this reason, as being also the most easily available witness of wrong, that in making a promise, an oath, or a curse (another form of promise), the one who promises or curses touches water. In the same way he may touch earth, as another divine witness. In the gift of a bride, not only "fire and hand-taking" but water are necessary, 7.55.15. So, in accepting a gift, one touches water, and hence "having wet hands" means having accepted a gift or bribe, 12.83.7, *ārdrapāṇi;* cf. *klinnapāṇi,* "one who has had his hand wetted," i. e. been bribed, 12.139.30. An example of touching water in uttering a curse is furnished by 3.10.32, *vāry upaspṛśya.* In the same way when the young knight's armor is bound upon him, the veteran instructor "touches water and murmurs a Mantra," 7.94.39. Almost every solemn act, such as committing suicide, 3.251.19; or installing a commander of an army, 8.10.45, in the *abhiṣeka,* 48; or using a fire (divine) weapon, 7.201.15, is thus introduced by touching water. For example, in 7.79.1–3, when Kṛṣṇa and Arjuna go to bed, they both touch water, and whenever they speak or think of Śiva, from whom they hope to get a favor, they touch water, *ib.* 80.17 and 22; and a little further, *ib.* 81.12, on touching the snake which is the apparent form of the Pāśupata (magic) weapon of Śiva, water is touched. On the death of a relative or on touching the corpse one must bathe at once; hence in 8.94.30, "when Karṇa was killed in battle the sun which had touched his bleeding body sank swiftly as if to take a bath (of purification) in the western ocean." Specially prepared, medicated, water is given to kings, but this is perhaps regarded as really medicinal, *kaṣāya* and *sādhivāsa* (*jala*), 7.82.10, as in 12.332.32.

Water is however magical on occasions. In 3.289.9f., it is related that a Guhyaka came from the White Mountain at the command of Kubera, bringing with him "water by means of which

you shall see all invisible things," *anena mṛṣṭanayano bhūtāny antarhitāny uta bhavān drakṣyati,* and, it is added, "he to whom you shall give it," that is, if he uses it as an eye-wash, he too shall see the invisible.

It is difficult to decide whether the power of water rests in every case on magic or on the feeling that water "of which the world is made," 1.180.18, and which is one of the three "purities" ("purity of speech, of deed, and purity consisting in water," 3.200.82) is a natural purifier. Water touched by a priest purifies from sin, 3.193.36, and this is the secret of most of the Tīrthas or sacred watering-places. They have been in contact before with some great saint or god and so won exceptional virtue.

But even plain water refreshes weary horses better if a Mantra (spell) has been said over it, 7.2.26.[16]

Water is especially associated with truth because truth is verbal purity. Consequently a very good man may walk over water or even drive his battle-car over water without sinking into it, as was the case with Pṛthu Vāinya, 7.69.9 and with Dilīpa, 7.61.9 and 10 (who was "a speaker of truth"). So too Yudhiṣṭhira's car did not sink upon earth till he told a lie, an analogous case with the divine earth instead of water as witness. The perjurer is cast out by the water in ordeals (passim).[17]

Magic Rites With Images.

The rite called *Chāyā-upasevana,* "shadow-cult," is explained by the commentator to be the well-known practice of sticking thorns or needles into the clay (wax) image of an enemy and thus inflicting pain or death upon the object of dislike. It is a clear case of "sympathetic magic." The commentor says it is explained in the

[16] Bathing "in different waters" at the end of a battle is of doubtful bearing; the water may be medicated, 6.86.54.

[17] Defilement of the water leads to the divine water's rejection of the sinner. So in Manu and other law-books. The defilement of water by casting into it excreta, saliva, etc., leads to the sinner's going to undesirable worlds, 7.73.31f. It is the fear of defiled water which causes the prohibition against living "in a village which has its water from only one well," 7.73.40. The crematory fire, when a corpse is burned, is extinguished with water, 8.20.50 (to keep off evil spirits).

Kāulika-Śāstra, 3.32.4. The South Indian recension has for this word a varied reading, the verse as there given being *ā mātṛstanyapānāc ca yāvac chayyopasarpaṇam* for the reading in B: *yāvad gostanapānāc ca yāvac chāyopasevanāt* (*janatavaḥ karmaṇā vṛttim āpnuvanti*). The adoration of the image of a teacher who has become estranged from his pupil is made in the hope that the image itself will act as the teacher, relent and give the desired instruction, and such proves to be the result in the one recorded epic case of Ekalavya who "made a teacher of earth, *mahīmaya*, and by cultivating it with the adoration due to a (real) teacher attained, through faith and devotion, to great skill in weapons" (which he sought by worshipping the earthen image), 1.132.33.

Authority for Magical Observances.

Apart from the magical practices mentioned above there is little which can be classed as magic in the Great Epic. Ceremonies to raise spirits are known and the use of a jewel, "which, when bound upon one, preserves from danger of all sorts" (weapons, sickness, hunger, gods, demons, serpents, etc.) is recognized, 10.15.29. But there is no essential difference between Mantras to make demons serve one and Mantras to control the gods, except that the latter are employed without ceremony by a woman and the former by a priest with the full paraphernalia of sacrificial ritual, *karma vāitānasambhavam*, 3.251.23 and 305.20. In both cases the rite is according to the Atharva Veda, as declared by Bṛhaspati and Uśanas, the teachers, respectively, of the gods and demons, that is, this Veda is the authority in all magical observances.

Of these two, it is the gods' teacher who has most to do with the magical practices recognized in the epic, which, so to speak, sets the seal of orthodoxy on the cult. From the epic texts hitherto known we may gather considerable information in regard to him. Bṛhaspati was the son of Aṅgiras, and the younger brother of Utathya; also the husband of Tārakā, and the brother of "that excellent lady who was the wife of Prabhāsa and the mother of the gods' great Artificer." He is reckoned among the Adityas and is identified with the fire-god, though he is also called a divine seer. His

knowledge in respect of raising the dead is inferior to that of Uśanas; but otherwise he seems to be more important than his rival. But the epic is too catholic to contrast the fourth Veda (of Bṛhaspati) with the others to their disadvantage except in one passage not hitherto known.

This passage is of great importance not only in what it says but in showing how the epic was composed. It is found only in the so-called Southern recension, and like most of the long interpolations in that recension is a late addition to the epic.[1]

In still another passage of this recension Bṛhaspati is represented as inculcating such extreme liberality as to say that a good Mleccha (barbarian) is better than a sinful Brahman; but in this particular addition he declaims against the other Vedas, which are all inferior to the Atharva as aids to the king. For the office of Purohit, king's priest, only an Atharvan priest should be chosen. The other Vedas have nothing to do with "pacificatory, auspicious, and evil-averting matters." These Vedas were "cursed by Yājñavalkya." Moreover: "The priest of the Rig-Veda is destructive to the realm; the Sāma-Veda priest is destructive to the king; and the Vājasaneyaka is destructive to the army." Here *abhicaraṇa* or sorcery is expressly mentioned as one of the objects to which the king's priest devotes himself. This passage, interpolated, together with an extract from Uśanas, into the seventy-third chapter of the twelfth book (thirty-seven verses between B.2a-b and c-d), goes far beyond the general rule of the epic, such as is given in 12.165.22, "Let one skilled in the Vāitāna be the *hotṛ*." It mentions eighteen kinds of pacificatory ceremonies and calls the Yajurveda priest the Vājin and Caraka, giving the preference to the former as the holder of the office of king's priest. After them are admissible the Rig-Veda and Sāma-Veda priests (as Purohits), provided they are duly conversant with the Atharva-Veda. All this means that the priest of the spell (*brahma*) must be preferred to all other priests for the ceremonies of magic and that the especial patron of this priest is the great "lord of the spell," Bṛhaspati, whose Veda is authoritative.

[1] On this point see a special article by the writer soon to be published on the Southern recension. The recension is a strong witness against the theory that the epic was composed "in one stream."

PHYSICAL NOTES ON METEOR CRATER, ARIZONA.

By WILLIAM FRANCIS MAGIE.

(*Read April 22, 1910.*)

1. Meteor Crater is situated near the center of the northern half of Arizona, six miles south of the line of the Santa Fe Road, about thirty miles east of Flagstaff. It is an immense hole or crater-like excavation in the otherwise level plain, nearly circular in shape, about 4,000 ft. across at the top, and surrounded by a rim of elevated strata and ejected material. This rim is from 120 ft. to 150 ft. high, and the floor of the crater is 570 ft. below its edge. From the edge there slopes down a very steep inclined talus, ending in the level floor.

The ejected material is mostly composed of broken and irregular limestone boulders from the higher stratum, some sandstone boulders from the next stratum, and an immense quantity of sandstone, which has been pulverized so that each grain of it has been broken into fragments so small that most of them will pass through a 200-mesh. The borings that have been made by the Standard Iron Company have shown that the interior of the crater is filled to a depth of 600 ft. or more with similar fragments of rock and with this pulverized sandstone.

The crater is the center of the area in which the Canyon Diablo meteorites have been found. These are of iron, carrying about 6 to 8 per cent. of nickel, and about three quarters of an ounce of platinum and iridium to the ton. They also contain microscopic diamonds, in large numbers, so that it is a work of great labor and difficulty to cut out a specimen for testing. Another variety of iron is also present, and judging from the residue of iron oxide which it has left, was originally present in much larger quantities than the Canyon Diablo iron. This differs from the Canyon Diablo iron in containing chlorine. It generally is found in oval or globular masses. It oxidizes readily, and forms sheets or plates of iron oxide, re-

sembling fragments of shale, so that it has been called by Mr. D. M. Barringer and Mr. B. C. Tilghman, who first recognized its meteoric origin, shale ball iron.

Through the kindness of the Standard Iron Company the author was given an opportunity to visit and study Meteor Crater. In this paper he desires to present the results of some of his observations, which have to do with physical problems presented by the crater. The description of the crater from the more general point of view, as a geological or cosmical phenomenon, has been given by Dr. G. K. Gilbert, of the U. S. Geological Survey, and by others. The demonstration that it owes its origin to the impact of a meteorite or group of meteorites was made by Mr. Barringer and Mr. Tilghman in papers presented to the Academy of Natural Sciences of Philadelphia, December, 1905, and with additional evidence by Mr. Barringer in a paper presented to the National Academy of Sciences, November, 1909. Professor H. L. Fairchild, of Rochester, and Mr. George P. Merrill, of the U. S. National Museum, have also studied the crater from this point of view.

2. *Magnetism.*—A cylinder 9 cm. long, 1.8 cm. in diameter was cut out of a Canyon Diablo iron, and tested for its magnetic permeability with a permeameter. The method is rough and unsatisfactory, but the only one which can be employed without either wasting too much work on shaping the specimen or possibly altering its condition by heating and working it. The values of H, the strength of field, and of μ, the magnetic permeability, are given in the following table, taken from the curve which best represents the observations.

H.	μ.	H.	μ.
4	400	12	530
6	455	14	505
8	500	16	472
10	533	18	442
10.5	540	20	405

Tests with a similar cylinder of Norway iron gave values for μ about double these, so far as the observations could be carried.

The pieces of shale ball iron at the author's disposal could not be prepared for the test with the permeameter. All that could be done

with them was to examine their behavior in the earth's magnetic field by the aid of a small magnet. They generally behaved like pieces of soft iron, or like pieces of the Canyon Diablo iron of about the same size.

A shale ball perhaps 9 in. in diameter, and which was entirely oxidized, was examined in position, soon after its discovery. It was found by excavating in the pulverized sandstone on the outer rim of the crater. It showed strong local poles scattered over its surface. In general, the polarity of the top was south, that of the bottom, north, but at many points the opposite polarity was found.

A piece of shale ball iron about 3 in. in diameter and 1 in. thick, when tested at the crater, showed north polarity all over the outer rim, and south polarity at two nearly opposite points on the two faces. This specimen was sent on to Princeton in a box with other specimens, and when tested again, this peculiar disposition of polarity no longer existed, and it now behaves like soft iron. This fact makes it improbable that the magnetic condition first observed was due to a superficial coating of magnetic oxide, and indicates that it was rather a real magnetic state of the iron. The shale formed from a shale ball by oxidation often shows very peculiar radial structure, and one is tempted to believe that this structure exists in the shale ball iron, and that it may be accompanied by a radial intrinsic magnetization. This view is borne out by some peculiarities of the magnetism of pieces of the shale, but the specimens of shale ball iron found are too few, and have been handled too much since they were found, to make it possible to test this view at present. Much of the shale is so feebly magnetic as hardly to affect a magnetic needle, even when close to it. Occasional pieces are strongly magnetic with well developed poles.

In 1891 Mr. Marcus Baker made a careful magnetic survey within the crater, and along lines running out on the plain. He found no evidence of any local magnetic field. The author ran some straight lines across the floor of the crater with a sensitive surveyor's compass, which could be read by estimation to about 2′ of arc, and found no variation in the compass deviation at different points on these lines. He also made a number of determinations

of the magnetic dip, using a Kew Dip Circle. The mean value of the dip found by fifteen observations was 62° 7.7′, with maximum variations at different points from the mean of —5.1′, and +4.2′. These variations may have been due to errors of observation, but are probably to some extent real and due to local conditions. There are several drill holes in the floor of the crater in which the iron pipes used in sinking the holes were abandoned, and these pipes could easily modify the general field to such an extent as to account for the different values of the dip which were found.

If the size of the meteor by which the crater was made is estimated by the old rules of artillery practice, we should conclude that it is equivalent to a sphere of about 750 ft. in diameter. A sphere of iron of this size at the appropriate depth below the floor of the crater would seriously affect the magnetic field. Even on the more moderate estimates of Mr. Barringer and Mr. Tilghman that it is equivalent to a sphere 250 ft. in diameter, the values of the dip at the extreme stations, at which the dip was observed, should differ by 30′. That no such difference was found argues that the meteor was broken and scattered by the impact, or more probably, as Mr. Barringer strongly argues in his latest paper, was a cluster or swarm of small masses of iron, mostly of the shale ball variety. The possible intrinsic magnetism of these masses, coupled with the possibility that they have gradually oxidized in the depths of the crater, would account for the absence of any observed magnetic field.

3. *Mechanical Effect of the Impact.*—When the map of the crater, showing the distribution of the ejected material, is studied, a remarkable symmetry of distribution is immediately apparent. A line drawn through the center of the crater, 13° west of north, can be taken as an axis of symmetry. This line on the north rim of the crater passes through or near the lowest part of the rim, and the region where the least ejected material is found. Its other end on the south rim passes through the middle of the greatest bulk of ejected material, which is furthermore found there in small fragments or largely in the form of pulverized sandstone, or "silica." Just to the east of it, where it has been driven by the

prevailing winds, is an area of brown sand, which the borings prove has come from the depths of the crater. The central line at right angles to this axis crosses the rim at or near the middle of two opposite areas on which the ejected material is deposited in large boulders, mostly of limestone, coming from the upper stratum of the formation. In two lines from the center 33° west and 42° east of this axis, toward the south, there lie out on the plain rows of limestone boulders, marked on the map as the furthest thrown limestone boulders.

The map showing the effect of the disturbance on the original strata exhibits this symmetry in another way. Starting where the axis crosses the northern rim, where the strata are inclined at only 5°, and proceeding around the rim in either direction, the strata gradually tilt more and more, reaching an inclination on one side of 50°, on the other of 80°. At about 135° around the rim on either side we find a fault and a short stretch in which the strata stand vertically. These two narrow regions are ended by faults which separate them from the remaining part of the rim, through the middle of which the south end of the axis passes. This portion of the rim is simply lifted about 100 ft. and the inclination of the strata is 0°. The lines of the furthest thrown limestone boulders are nearly over the two regions in which the strata are vertical.

The experiment was tried of shooting a half inch spherical lead ball from a high-power rifle into a level floor of smooth densely packed silica. The inclination of the shot was about 30° from the vertical. The tilting of strata, of course, could not be observed; but the distribution of ejected matter on either side of the plane of incidence was remarkably like that described in the preceding account of the crater. The greatest amount of finely powdered material formed a rim to the shallow hole, ahead of the bullet. The edge over which the bullet passed had little or no matter piled up on it. The edges diametrically opposite, across the line of flight, were lined with powder and many lumps of silica, still forming definite masses, though the material is so friable that it was hard to pick up one of these lumps with the fingers without crushing

it to powder. On either side of the plane of incidence, making angles with it of about 40°, were many fine marks or scratches in the smooth floor, showing where small particles had been driven ahead with great violence. The hole had sloping walls and an inner level floor. A sketch map made from the bullet hole and a map of the crater in which only those details are preserved which the bullet hole can show, are remarkably similar.

The theory of the strains which would end in such a distribution of the broken material ejected by an impact cannot be given; but the observations direct attention to some interesting peculiarities. The piling up of most of the ejecta ahead of the projectile is what might be expected, but it is less obvious that the stresses should be so distributed as to break up the material on either side of the line of flight into separate blocks and arrange them on either side of the hole along the rim. The two spurts of small fragments, thrown out forward diagonally from the line of flight, are also remarkable.

The lead bullet used was torn to fragments, and much of it was flung out of the hole. The other bullets tried, of other material, were generally badly deformed and torn; and were thrown backwards out of the hole, either whole or in fragments. The steel bullets were the only ones which retained their shape, and they remained buried in the holes made by them. It does not seem probable that much, if any, of the meteor which made the crater was thrown out of it in a similar way.

4. *Energy.*—The data from which to determine the energy with which the meteor struck the earth are not precise; but an estimate can be made of the energy with some degree of plausibility.

The work done in excavating the crater is insignificant in comparison with that done in crushing the rock. The mass ejected may be estimated at 330 million tons (of 2,000 lbs.). This is considerably more than the mass excavated in the construction of the Panama Canal. The bottom of this mass was 500 ft. below the original surface. To lift the mass up and clear of the hole would probably use 16×10^{10} ft. tons. Something more must be added for the work of tilting back the strata and lifting the unbroken

rock masses all around the rim to a height of 100 ft. Perhaps 20×10^{10} foot tons spent in mechanical lifting would not be an overestimate.

Most of the energy was spent in breaking up the rock, and especially in shattering the grains of sandstone into the very finely pulverized silica. Only a rough guess can be made of the amount of this silica, but large parts of the ejecta consist of little else, and the borings have shown that the crater also contains great quantities of it. From the probable size and shape of the whole cavity it appears that over 500 million tons of rock were broken up. Of these, perhaps one fifth, or 100 million tons, are in the form of pulverized silica. The work done when this silica was formed was expended in separating the particles and in rubbing them over each other. The work done against friction must have been retained as heat. The temperature generally did not rise to the melting temperature of quartz, for the grains of silica rarely show evidence of fusion. A small quantity of melted quartz is found, which is full of blow holes, as if, when melted, the mass had been pervaded with an expansible vapor. One way of explaining this formation is to suppose that it represents the fusion of the shattered quartz in the presence of water, which is known to be present occasionally in pockets in the generally dry sandstone, the superheated steam formed at the same time accounting for the porous state of the material. If this explanation is correct, it indicates that the temperature of much of the silica was nearly that at which quartz melts when dry, and above the temperature at which it melts in the presence of water. If we set, as an outside limit of temperature, 2500° C., and suppose all the silica heated to that extent, the heat developed is equivalent to 9.25×10^{13} ft. tons. It is possible to ascribe the melting of the quartz to the heat more directly developed in the neighborhood of the advancing meteor. In this case it is more difficult to fix a lower limit of temperature for the silica. The iron found outside the crater in the silica shows no evidence of melting, and the Widmanstatten figures are preserved. If we assume the general temperature of 625°, to keep it not only below the melting point of iron, but also below that temperature

at which the Widmanstatten figures disappear, the heat developed in the silica would then be equivalent to 2.3×10^{13} ft. tons.

The work done in the silica is surely only a fraction of the whole. A layer of hard limestone, 300 ft. thick, was also broken up, and much of it must have been pulverized also. After all, we can do no better than guess; but taking all the work done into account we may, in my opinion, estimate it without exaggeration, at 60×10^{12} ft. tons.

Such a projectile as would have made the crater would have reached the earth without retardation by the atmosphere. If it were moving, as a comet does, with the parabolic velocity of 25 miles a second, and were to encounter the earth head on, it might fall with a velocity something over 43 miles a second. We may set the outside limits of velocity at 3 and 48 miles a second. With the lowest velocity the mass required to bring in the estimated energy is 15×10^6 tons; with the highest velocity only 60,000 tons.

The mass of the meteor may otherwise be estimated from the size and shape of the crater. Experiments with cannon shot, quoted by Mr. Tilghman, show that with velocities of 1,800 ft. a second, the depth of the hole made in limestone rock is about twice the diameter of the shot, and its width at the top about five times the diameter. These proportions were well borne out by observations with spherical rifle balls shot into sandstone. If these proportions held for the crater they would indicate a projectile 750 ft. in diameter, with a mass of about 50×10^6 tons. This is evidently an over-estimate. The mass indicated in this way is however of the same order of magnitude as the greatest mass indicated by the estimates of the energy and velocity. Manifestly the extreme velocities estimated are not probable, so that the mass is probably neither so large nor so small as the extreme values obtained. A mass of 400,000 tons moving with a velocity of from 18 to 20 miles a second would bring in the estimated amount of energy. In the absence of other evidence this seems a reasonable mass to assign to the buried meteor.

THE CONVERSION OF THE ENERGY OF CARBON INTO ELECTRICAL ENERGY ON SOLUTION IN IRON.

By PAUL R. HEYL.

(*Read April 22, 1910.*)

In molten iron carbon dissolves with a liberation of energy, which, by providing a suitable negative electrode, may be obtained in the form of an electric current. The resulting electromotive force is quite small, but is clearly to be distinguished from the accompanying thermo-electric effect.

The experiment about to be described was, in outline, to set up a voltaic cell consisting of electrodes of wrought iron and carbon immersed in a bath of molten iron or steel of a low carbon content. Such an experiment is beyond the equipment of an ordinary laboratory, and for its execution I am indebted to the courtesy of Dr. Geo. W. Sargent, of the Carpenter Steel Company, Reading, Pa., who placed the necessary facilities at my disposal.

The ideal liquid for such a cell would be a carbonless iron, just as fresh acid in an ordinary cell is more effective than one which already contains some zinc in solution; but the melting point of such iron is too high to be reached in a steel furnace. It was, therefore, necessary to employ a low carbon steel. On account of its higher melting point wrought iron furnishes a convenient material for the negative element.

The positive element was built up of three carbon rods, such as are used in arc lights, wired firmly to a copper rod at their upper ends. Two such electrodes were prepared in case one should crack in the melted metal. To minimize as much as possible the danger of cracking, the carbon was gradually heated by placing it at first near, and finally in, an empty red-hot crucible. In this way the tips of the rod were made red hot.

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Having no milli-voltmeter at my disposal it was necessary to use a milliammeter, which of course is equivalent to the other if the resistance of the circuit is known. Connections were made to the ammeter on the supposition that the current would leave the cell by the wrought iron electrode and return by the carbon. Care was taken, however, to insert a reversing key in the circuit.

About ninety pounds of a low carbon steel (0.10 per cent.) were placed in a crucible and heated for about four hours. Perfect fluidity could not be obtained, but the mass finally became pasty and viscous, allowing a rod of iron to be plunged into it without great difficulty. A small amount of aluminium was then added to free the mass from gas bubbles, and the crucible was then withdrawn from the furnace, placed on the floor and banked about with coal, which immediately took fire. As quickly as possible, for the metal rapidly hardened, the electrodes were plunged in while a watch was kept at the ammeter.

Almost immediately the carbon electrode snapped off at the surface of the metal, and so rapid was the cooling that by the time the spare carbon electrode could be brought into action the metal was too hard to allow it to be plunged in; but the small fraction of a second available to the watcher at the ammeter was sufficient.

Immediately on plunging in the carbon electrode the pointer of the ammeter started to move in the expected direction. When the carbon cracked the reading was 0.015 ampere. The pointer then fell back and exhibited a tendency to a reverse deflection. Turning the reversing key, the pointer again moved forward and remained stationary at about one third of its previous reading. On looking at the crucible it was found that the upper portion of the electrode was lying loosely upon the surface of the now solid, though still red-hot metal. On lifting the electrode the deflection disappeared, but reappeared as often as the carbon was touched to the hot metal or even to the (now hot) iron electrode. This deflection was plainly of a thermo-electric origin, while the earlier deflection in the opposite direction is to be explained only as the result of galvanic action.

How far the pointer would have moved had the carbon not

cracked it is, of course, impossible to say. Neither is it possible to be certain as to the voltage corresponding to the observed reading of 0.015 ampere. The resistance of the ammeter and lead wires together was less than one ohm, and the uncertainty lies in the resistance of the hot metal and the contacts with it. The electrodes were about 15 cm. apart, and the crucible had a diameter of some 25 cm., so that, although the temperature was high, the resistance must have been very small. One ohm would probably be a liberal allowance. Assuming a total resistance of two ohms in circuit, the voltage would have been 0.03.

On general principles, we should expect that any such voltage would be very small. That there is any liberation of energy at all when carbon dissolves in melted iron indicates that the act of solution is, at least in part, chemical, and points to the existence of a new carbide of iron, stable at high temperatures, and of a simpler molecular formula and greater energy content than the well known carbide Fe_3C, which is stable only below a red heat, just as CO stands between CO_2 and free carbon and oxygen. Now the heat of formation of Fe_3C is not known, but its energy content must be but little less than that of its constituents in a free state; and consequently the margin of liberated energy at the formation of the hypothetical simpler carbide must be extremely small.

Further experiments on this matter are in progress.

THE ETHER DRIFT.

By AUGUSTUS TROWBRIDGE.

(*Read April 22, 1910.*)

At one time in the course of the development of physical science there were almost as many ethers postulated as there were phenomena to be explained. "Ethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of the body to another, till all space was filled several times over with ethers" (J. C. Maxwell).

Of all these ethers the only one which has survived to our day is that of Huygens which is, so to speak, working over-time in that it has to serve the electrician as well as the optician and it is rather disheartening to think that after more than one hundred years of unremitting labor all that we really know of its properties is this—it transmits any electro-magnetic disturbance with the speed of three hundred million meters per second.

When we admit the hypothesis of the ether with this property the question arises as to the nature of the mechanical bonds between ether and matter—there are of course three possibilities—when matter is in motion either the ether moves with it completely, or it is partially entrained or it is not entrained at all.

The simplest of these three possibilities is perhaps the first—that the ether is completely entrained by the moving matter—it is the simplest hypothesis because it would mean that matter, once associated with a given quantity of ether, remained so forever and if this were the case we might hope to explain matter in terms of the ether indissolubly associated with it. Unfortunately the celebrated experiment of Fizeau on the change of velocity of light with and against a stream of moving transparent matter rules out this simplest hypothesis of complete entrainment and leaves us the choice of an ether which is partially entrained by moving matter or one which is a rest absolutely and not entrained at all.

The reason why we are left with these *two* possibilities is that the increased velocity of propagation of light in the direction of the moving matter which Fizeau clearly demonstrated by direct experiment may be due to the ether being dragged by the moving matter or again it may be that the ether is at rest while the matter moving through it in some way affects the speed of propagation of light.

It has been found impossible to develop a theory based on the first of these possibilities as an hypothesis without introducing very arbitrary assumptions as to the relation existing between the ether and moving matter but if the second possibility be adopted as an hypothesis, viz: the ether at rest in space; it has been found possible, by the Dutch physicist, Lorentz, to develop a theory without further arbitrary assumptions which is in accord with results of a considerable number of optical experiments.

If the ether be at rest it will be in motion relative to the earth as it moves in its orbit and one might expect to find a different velocity of propagation of light according as it is measured with or against the supposed drift of the ether. The effect to be expected will depend on the ratio of the velocity of the moving earth to the velocity of light—this ratio in round numbers is one ten-thousandth. There are many ways of detecting a variation in the velocity of light by this amount and a number of physicists have attempted to detect such a charge according as the velocity was measured along or across the direction of the supposed ether drift. All these experiments have given negative results and it is in favor of the theory of Lorentz that it explains the absence of this so-called first order effect when the light source and the observer are in motion together, but even on the Lorentz theory there should be an effect observable under these conditions which is proportional to the square of the ratio of the earth's velocity to the velocity of light—that is, proportional to one one-hundred millionth. This is called a second order effect.

Messrs. Michelson and Morley devised an experimental arrangement of sufficient sensitiveness to detect a second order effect due to relative motion of the earth and the ether, and they concluded that the earth must drag the ether along with it in its motion.

The results of this justly celebrated experiment of Michelson and Morley cannot be reconciled with the one theory which is in accord with the other optical phenomena such as stellar aberration and the Fizeau experiment, and which we have seen postulates an ether at rest in space and so it became necessary either to abandon the theory or to explain why the second order effect predicted by the theory should not have been detected in the Michelson-Morley experiment.

This explanation, due to Lorentz and Fitzgerald, was based on an assumed shortening of the linear dimensions of matter resulting from its motion through the ether. It is true that effects necessarily attendant on this hypothetical shortening have been sought in vain, but nevertheless this so-called Lorentz-Fitzgerald objection has tended to discredit the conclusions of Messrs. Michelson and Morley.

This, then, was the state of the question as to the relative motion of matter and ether when Professor C. E. Mendenhall and I undertook, in 1905, the work on which I am reporting at this time. (1) A well-developed theory based on the assumption of a stagnant ether which predicts a second order effect when the source of light and observer are in motion with respect to the ether. (2) Failure to detect any such effect by Michelson and Morley and the conclusion by them that the ether is at rest relatively to the moving earth and hence not stagnant. (3) The theory rehabilitated by an assumption that the linear dimension of matter is shortened by an amount of the second order when it moves through the ether. (To support this assumption good theoretical reasons were later adduced.)

In further experimentation it was obviously necessary to devise apparatus which should give indications which were independent of any hypothetical change of dimensions such as that suggested by Lorentz and Fitzgerald and be nevertheless sufficiently sensitive to detect the optical second order effect due to its motion relative to the ether.

The device adopted by us consisted of a source of light placed midway between two delicate electrical thermometers. Suppose the line joining the three points to lie in the direction of the motion

through space of the point of the earth's surface where the apparatus is set up, and suppose the relative positions of the three points be such that each thermometer receives the same amount of radiation from the source of light which lies between them. Now, if the ether be drifting across the apparatus in the direction joining the three points as the theory of Lorentz would have it drift, and if thereby the dimensions of the apparatus in this direction be shortened as Lorentz and Fitzgerald have supposed it to be shortened, *then* if the whole apparatus be rotated 180° about a vertical axis the distance between the three points cannot have altered so that if any change in the amount of radiation received by the two thermometers were to be noticed on rotating the apparatus through 180° it might be taken as proof positive that the ether was in motion relative to the apparatus. On the other hand, if the apparatus were sufficiently sensitive to detect a second order optical effect and no change took place on rotation, the objection could not be made that the effect was there but had been masked by shortening, since no hypothetical shortening could be conceived to alter the relative positions of three points on a straight line.

Thus the problem which confronted us was to devise apparatus capable of detecting a change in radiation received by its two parts so small as one one-hundred millionth part of this radiation—expressed differently it was to devise a pair of electrical thermometers capable of detecting a difference of temperature of less than the ten-millionth part of a degree and yet to so protect them that in spite of the fact that they must stand several feet apart that they should be subject to no irregular fluctuation in temperature of this order of magnitude. Also they must be mounted on a support so rigid that it may be rotated without introducing irregularities due to change of shape. After considerable trouble we have succeeded in satisfying both these conditions, but there remains a third more difficult condition which we have as yet not been able to wholly satisfy—this is that the two conditions just mentioned must remain satisfied when the thermometers are subjected to radiation from a light source standing between them which is at a

white heat and getting rid of energy at the rate of about one half a horse power.

In conclusion I would say that we confidently expect to be able to reduce the irregularities due to, as yet, uncontrolled temperature fluctuations—these now amount to about 8 times the effect we seek —two years ago they amounted to 1,000 times this effect.

CHARACTERISTICS OF THE INLAND-ICE OF THE ARCTIC REGIONS.

(PLATES XXVI–XXX.)

BY WM. HERBERT HOBBS.

(*Read April 22, 1910.*)

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The Arctic Glacier Type.

Introduction.—As elsewhere pointed out, continental glaciers are in other than dimensional respects sharply differentiated from those types which have been described as mountain glaciers.[1] The ice-cap glacier, while of smaller dimensions than the true inland-ice or the continental glacier, is yet distinctly allied with this type, and has few affinities with mountain glaciers. The sharpness of the distinction has often been overlooked for the reason that true mountain glaciers frequently exist within a fringe surrounding the larger areas of inland-ice both in the Arctic and Antarctic regions. The distinguishing difference between mountain glaciers and continental glaciers is one primarily dependent upon the proportion of the land surface which is left uncovered by the ice, and the position of this surface relative to the margins of the snow-ice mass. *With true mountain glaciers land remains uncovered above the highest surfaces of the glacier, where, in consequence, a special erosional process—cirque recession—becomes operative.* The smaller ice-caps take their characteristic carapace form and cover the surface of the land within their margins, because that surface is relatively level. Had it been otherwise, the same conditions of precipitation would have yielded mountain glaciers in their place. The law above stated is none the less applicable, since because of this flat basement no land projects above their higher levels.[2]

[1] Wm. Herbert Hobbs, "The Cycle of Mountain Glaciation," *Geogr. Jour.*, Vol. 35, 1910, pp. 147, 148.

[2] With a keenness of insight which has rendered the descriptions of his travels particularly valuable, Sir Martin Conway has pointed out the main distinction here expressed. His explanation of cirque formation, which he

There are, as we shall see, other attributes which strikingly differentiate the large continental glaciers from all other bodies of land ice. These relate particularly to the nature of the snow which feeds them, to changes which that snow undergoes after its fall, to the manner of its transportation, etc. Most of these differences are of such recent discovery, or at least of such recent introduction into the channels of dissemination of science, that they have not yet found their way to the student of glacial geology. We shall profitably begin our description of continental glaciers with the intermediate ice-cap type, so as to establish connection with mountain glaciers in the important condition of alimentation. Before doing so, it will be well to call attention to some contrasts which exist between the north and south polar regions in those conditions upon which glaciation depends.

North and South Polar Areas Contrasted.—A glance at a globe, which sets forth the land and water areas of the earth, is sufficient to show that the disposition of land and water about the opposite ends of the earth's axis is essentially reciprocal. About the north pole we find a polar sea, the Arctic Ocean, surrounded by an irregular chain of land masses which is broken at two points, nearly diametrically opposite. In the Antarctic region, on the contrary, it is a high continent which surrounds the pole, and this is bounded on all sides by a sea in which are joined all the great oceans of the globe. This polar continent is deeply indented on two nearly opposite margins, but to what extent is not yet known. The margins of the continent are extended beneath the sea in a wide continental shelf or platform. The broad encircling ocean, while to some extent invaded by the southern land tongues of South America, Africa, Australia and New Zealand, is yet so little occupied by land masses that wind and ocean currents are alike but slightly affected by them. The Antarctic conditions are, therefore, oceanic—characterized by uniformity and symmetry to a much larger extent than is true of the northern polar region.

clearly recognized to be a result of sub-aerial disintegration rather than erosion, is however, practically that advanced by Richter, since it takes no account of the bergschrund. (W. M. Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, Vol. 12, 1898, pp. 142–147.)

Within the northern hemisphere a large quantity of heat from the tropics finds its way northward to the breaks in the northern land chain, through the medium of great ocean currents—the Gulf Stream in the Atlantic, and the Japanese Current in the Pacific. Cold return currents from the Arctic region, and the widely different specific heats of land and water, coöperating with the effect of the northward flowing warmer currents, result in a marked diversity in temperature, winds and precipitation at different longitudes within the same latitudes. Lack of symmetry in distribution and wide variations in climatic conditions are, therefore, characteristic of the north polar region; and it follows that the present glaciation of the northern hemisphere is localized within a few scattered areas where the land projects farthest toward the pole and near where there are sea areas of excessive evaporation to supply the necessary moisture.

The Fixed Areas of Atmospheric Depression.—Examination of Fig. 1 will show that the areas of existing heavy glaciation in the northern hemisphere lie close to the so-called fixed areas of low barometric pressure, each of which is a long, curved trough, concave to the northward, one central over the Aleutian Islands' Arc at the northern bay of the Pacific Ocean, the other extending from the southeastern extremity of Baffin Land past Cape Farewell, and northeastward across Iceland, so as to occupy similarly the northern bay of the Atlantic Ocean. For such northern latitudes these areas of fixed low barometric pressure are in consequence characterized by abnormally large evaporation. Wherever the moisture-laden winds proceeding from these areas are forced to rise by upland barriers, or to come in contact with cold rock or snow surfaces, condensation and precipitation must inevitably take place.

The prevailing westerly winds from the Pacific, when they encounter the high backbone of the Cordilleran System of mountains in Alaska nourish the great mountain glaciers of that region. The Cordilleras of Alaska are, however, competent to arrest but a small portion of these moisture-laden clouds, for it is only in moderate latitudes that they bar the way, and no highlands lie

beyond them to the eastward until the vicinity of Baffin Bay has been reached.

On the border of the Atlantic low pressure area are found Greenland, Iceland, Spitzbergen, Norway, Franz Josef Land and Nova Zembla, each with its upland areas and its existing glaciation. In Norway, Iceland, and Franz Josef Land we find ice-caps; in Spitzbergen, Nova Zembla, Baffin Land, Grinnell Land and Ellsmere Land, the mantle of snow and ice is best described by the

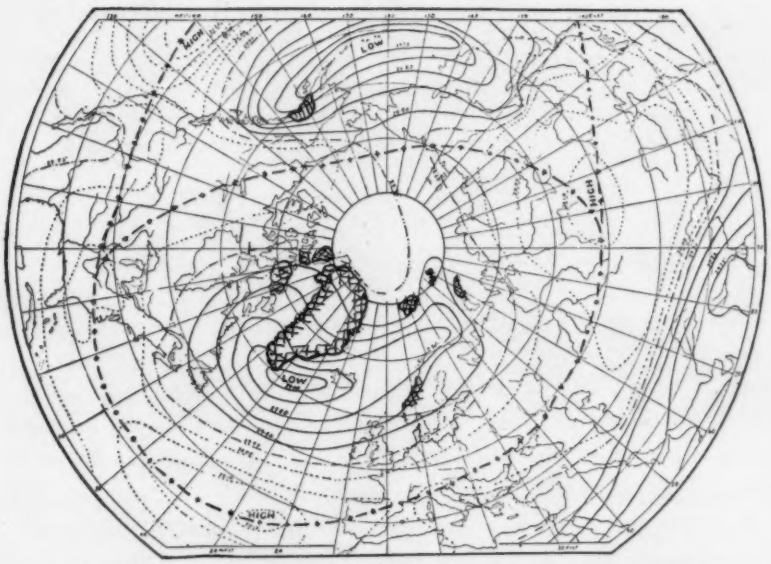

FIG. 1. Map showing the areas of fixed low barometric pressure in the northern hemisphere (after Buchan). The areas of heavy glaciation have been added.

name inland-ice, while upon the continent of Greenland the inland-ice has continental dimensions and forms one of the two continental glaciers that still exist.

Of all the northern ice sheets, with the exception of the Archipelago of Franz Josef Land, the rule holds that they are smaller than the land masses upon which they rest, and this in part expresses the difference between the northern and southern types of inland-ice.

Ice-caps of Norway.—In contrast with all save the Piedmont type of mountain glaciers, the snow fields of ice-caps are much the larger. Speaking broadly, high and relatively level plateaus, light winds, and low temperatures are favorable to the existence of ice-caps. Today they are not to be found in latitudes lower than 60°. In Norway, within the zone of heavy precipitation along the western coast, and upon the remnants of the plateau separated by the fjords, are still to be found a number of small ice-caps. These caps consist of a central carapace of snow and ice from the borders of which narrow tongues descend into the fjords. The largest of these ice-caps is the Jostedalsbraen, having an area of 1,076 square kilometers. Whereas with mountain glaciers the névé is contained within a basin, the cirque, we here find the so-called "fjeld" nearly level and resting upon the surface of the plateau. Of this fjeld broadly lobate extensions lie upon its margin separated by deep valleys or fjord heads. Much narrower extensions of the central carapace often descend the steep slopes at the upper end of these valleys and may continue down the valley floor. Their narrowness is largely explained by their more rapid motion upon the steeper slope and by the reflected heat from the rock walls on either side. See Fig. 2.[3]

FIG. 2. Idealized section showing the form of "fjeld" and "brae" in Norwegian ice-cap.

Ice-caps of Iceland.—In Iceland are to be seen some of the finest examples of ice-caps that are known, and, fortunately, these have been carefully studied by Thoroddsen.[4] These ice-caps form gently domed crests or undulating ice fields situated upon the

[3] H. Hess, "Die Gletscher," 1904, pp. 66, 99–92.

[4] Th. Thoroddsen, "Island, Grundriss der Geographie und Geologie," *Pet. Mitt.* (Ergänzungshefts 152, 153), 1906, V., "Die Gletscher Islands," pp. 163–208.

highest plateaus which rise above the general table-land of the country. Projecting mountain peaks appear with few exceptions only near the thinnest margins of the ice, where they form either comb ridges or sharp peaks (see Figs. 3 and 4). White and altogether free from surface rock débris except in the vicinity of their margins, these ice-caps offer in this respect additional contrast to mountain glaciers. The largest of the Iceland ice-caps is the Vatna Jökull, which has an area of 8,500 square kilometers,

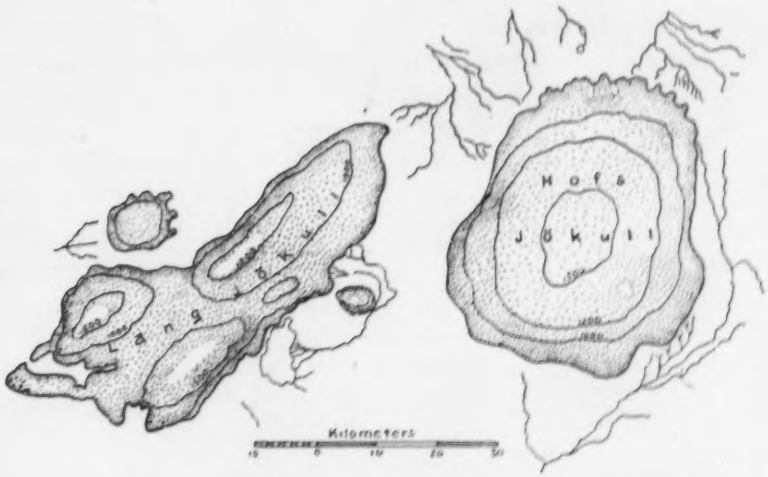

FIG. 3. Maps of the Hofs Jökull and the Lang Jökull (after Thoroddsen).

while the surfaces of the Hofs Jökull, Lang Jökull and Myrsdals Jökull each exceed a thousand square kilometers. The shield-like boss of the Vatna Jökull is brought out in the section of Fig. 5.[5]

Those borders of this ice mass which lie upon the plateau, the northern and western areas, are broadly lobate; but upon the southern and eastern margins, where the ice mass descends to lower levels and approaches the sea, its tongues sometimes end a few meters only above sea level. It is noteworthy, however, that where deeply incised valleys invade the plateau upon this margin, the lobes of ice push out mainly upon the upland remnants between

[5] Hans Spethmann, "Der Nordrand des isländischen Inlandeises Vatnajökull," *Zeitsch. f. Gletscherk.*, Vol. 3, 1909, pp. 36–43.

the valleys, though they send narrow tongues down the valleys themselves. This, as we shall see, is a peculiarity which ice-caps and the northern inland-ice as well have in common to distinguish

FIG. 4. Map of the Vatna Jökull (after Thoroddsen).

them further from mountain glaciers. As was found true of the Norwegian glaciers, so here the tongue which follows the valley bottom and which partakes of many of the properties of a mountain glacier, is much the narrower.[6]

From the north or plateau margin of the Vatnajökull flow mighty but sluggish streams which near the glacier are braided into constantly shifting channels within a broad zone of quicksand. In this sand, horse and rider if once entangled are quickly lost. Upon the south margin, on the other hand, the streams from the melt-

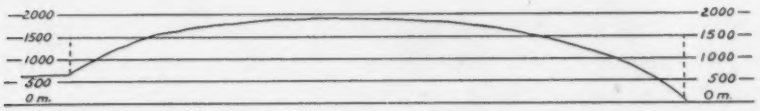

FIG. 5. Cross section of the Vatna Jökull from north to south (after Thoroddsen and Spethmann).

ing of the ice flow as fast rushing rivers, sometimes so broad as not to be bridged, and in these cases setting up impassable barriers between districts.

Icelandic ice-caps differ from all well-known glaciers at least in this, that nowhere else are large ice masses in such direct association with so active volcanoes. The *jökulhlaup*, which is the Icelandic name applied to one of the characteristic catastrophies of the island, occurs whenever a volcano, either visible in the neighborhood of the glacier or hidden beneath it, breaks suddenly into eruption. The first intimation that such an event is transpiring, is often the drying up of a stream which flows from the affected region. Sometimes the people are permitted to see great masses of lava and volcanic ash issue together from the glacier. All at once, the stream which had first dried up comes rushing down its valley as a foaming flood of water, spreading out for miles and having a depth sometimes as great as 100 feet. The entire plain is then spread with mud and sown with great rocks and also with ice blocks, some of which are as large as the native houses. These ice blocks are

[6] Carl Sapper, "Bemerkungen über einige südisländische Gletscher," *Zeitsch. f. Gletsch.*, Vol. 3, 1909, pp. 297–305, two maps and three figures. See especially Fig. 3.

often buried in the mud, and later, when they have melted, they leave deep pits in the plain similar to though smaller than the depressions in a "pitted plain" from the continental glaciers of Pleistocene time.

During such an eruption, water has been seen to shoot up from the glacier in great jets, and it has sometimes happened that the entire ice mass of the jökul has been shattered, and a chaotic mass of ice miles in width has slipped resistlessly down the slopes. With the conclusion of the disturbance, the aspect of the entire district is sometimes found to be utterly changed. All vegetation has been destroyed, and ridges which had lent to the landscape its character have vanished, so that streams have lost their old channels and entered upon wholly different courses.[7]

Ice-covered Archipelago of Franz Josef Land.—The islands of Franz Josef Land in the high latitude of 80° and over, with altitudes of 2,000 to 4,000 feet and situated as they are on the borders of an open sea, are the most Arctic in their aspect of all the smaller northern land masses. As a consequence, they are with unimportant exceptions completely snow capped, the snow-ice covering sloping regularly into the sea upon all sides. The Jackson-Harmsworth[8] and Ziegler[9] expeditions, following those of Nordenskiöld, Nansen, the Duke of the Abruzzi, and others, have now supplied us with fairly accurate maps of all islands in the archipelago. One or two of the western islands alone show a narrow strip of low shore land, but with these exceptions all are covered save for small projecting peaks or plateau edges near the ice margins (see Fig. 6). They present, therefore, a unique exception to the law which otherwise obtains, that within the northern hemisphere glacial caps are smaller than the land areas upon which they rest. The appearance of the island covers is here, however, that of névé of low density, rather than of compact glacier ice.

Prince Rudolph Island, which was the winter station of the Italian polar expedition, is no doubt typical of most islands in the

[7] Otto Nordenskiold, "Die Polarwelt," 1909, pp. 42–43.
[8] F. G. Jackson, "A Thousand Days in the Arctic," 1899, map 5.
[9] Anthony Fiala, "The Ziegler Polar-Expedition of 1803–5," 1907, map C.

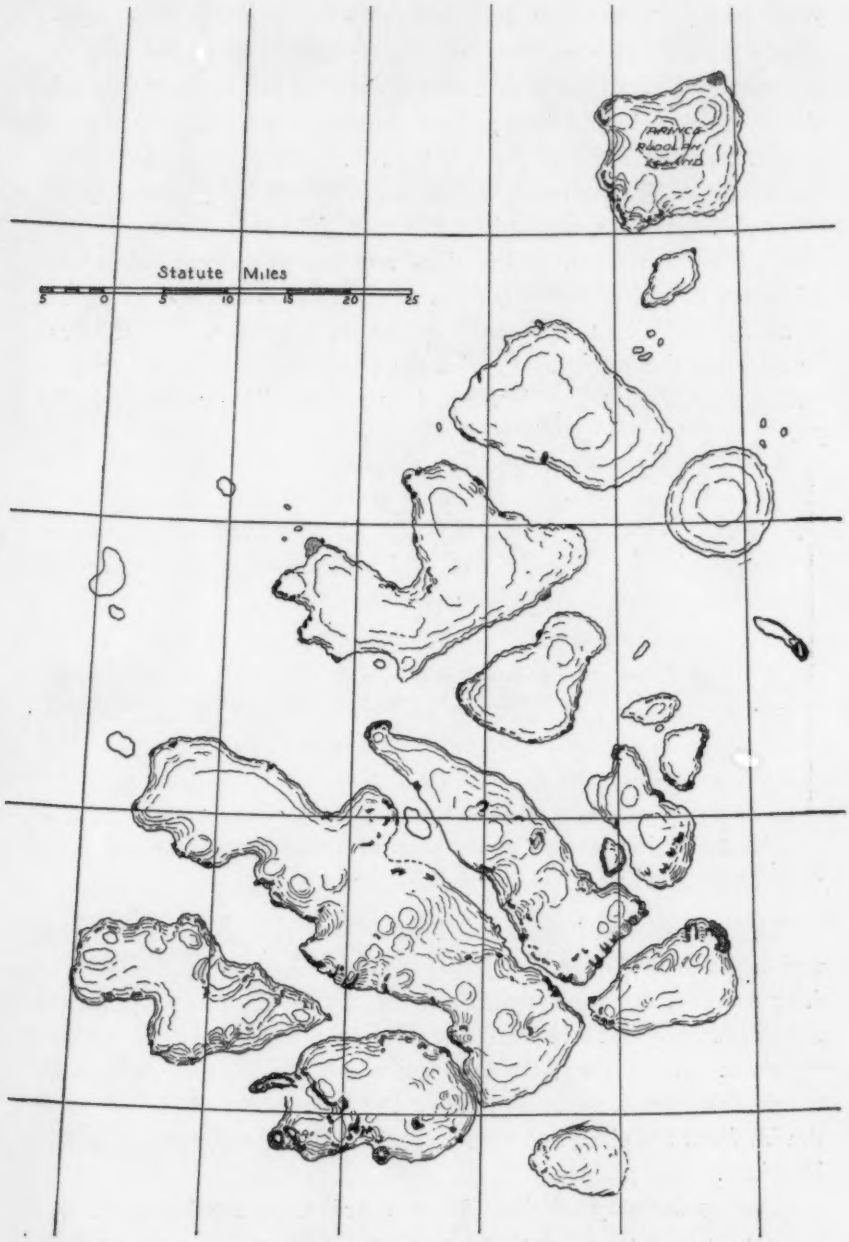

FIG. 6. Map of the ice-capped islands in the eastern part of the Franz Josef Archipelago (after Fiala).

archipelago. This island is described by Duc d'Abruzzi[10] as "completely buried under one immense glacier, which descends to the sea in every direction except at a few points, such as Cape Germania, Cape Säulen, Cape Fligely, Cape Brorok, Cape Habermann and Cape Auk. At some of these points, . . . the coast is almost perpendicular, which prevents the ice from descending to the sea. At others, . . ., the ice, stopped by a hollow, falls into the sea on each side of the headland, which thus remains uncovered. Moreover, wherever the snow can rest, there are glaciers which end at the sea in an ice-cliff, like that formed by the main glacier, so that it can be said that the entire coast, with the exception of a short extent of strand near Teplitz Bay, is formed by a vertical ice-cliff" (see Fig. 7).

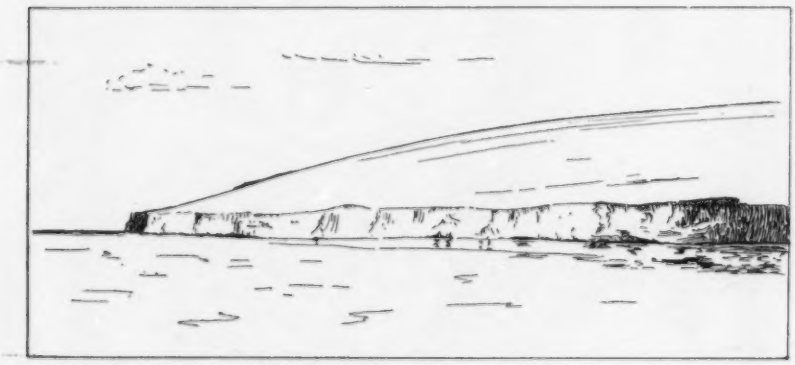

FIG. 7. Typical ice cliff of the coast of Prince Rudolph Island, Franz Josef Land (after the Duke of the Abruzzi).

The movement of the ice is so slow that though a line of posts was established for the purpose of measuring during a period of four months, no movement could be detected. Except near the outermost margin, there were few crevasses, and these were covered by snow. In summer, on days when the temperature was above the freezing point, the snow thawed rapidly so that torrents of water flowed from the glacier to the sea, hollowing out channels many feet in width.

During the stay of the "Polar Star" near the island, it was

[10] On the "Polar Star" in the Arctic Sea, 1903, Vol. 1, pp. 116–118.

noteworthy that thaw and evaporation upon the island exceeded the precipitation. Doubtless because of the slow movement of the ice, no icebergs were seen to form during the entire stay.

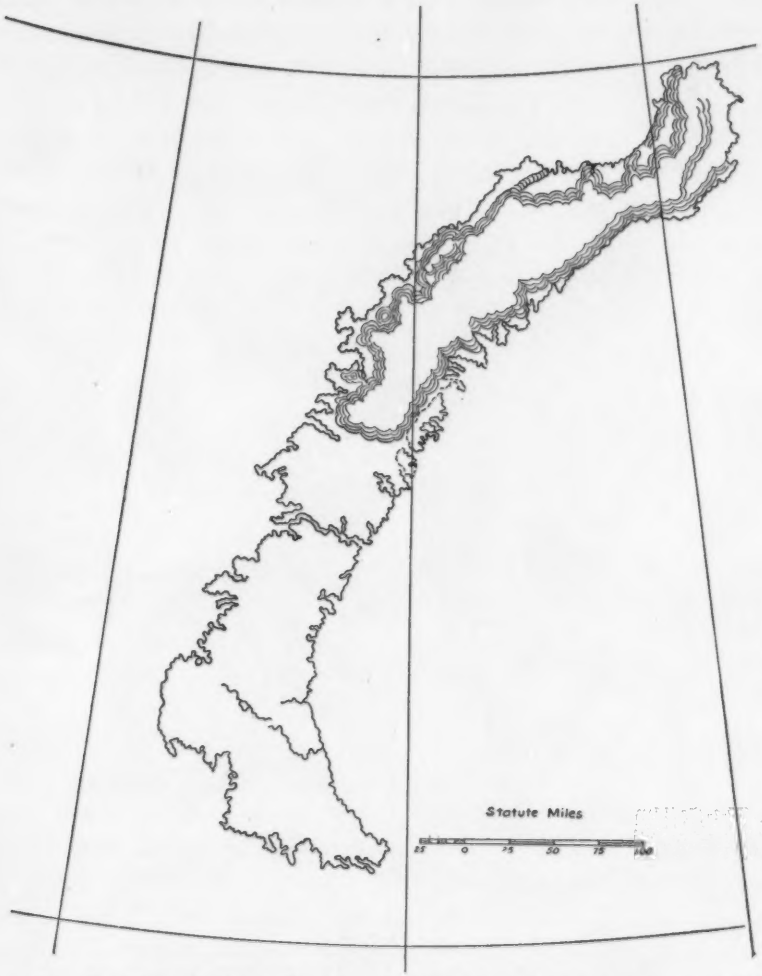

FIG. 8. Map of Nova Zembla, showing the supposed area covered by inland-ice (from Andree's "Handatlas").

The Smaller Areas of Inland-ice Within the Arctic Regions.— The ice-cap of the Vatna Jökull in Iceland, which is the largest to

which this name has been applied, covers an area of 8,500 square kilometers. Ice carapaces which are better described as inland-ice, since they cover considerable proportions of the interiors of the land areas upon which they rest, occur to the northward of Europe in Nova Zembla and Spitzbergen, and in the lands to the west of Baffin's Bay, known as Baffin, Ellesmere, and Grinnell lands.

FIG. 9. Map of Spitzbergen, showing the supposed glaciated areas (from Andree's "Handatlas").

Nova Zembla is a long, narrow island, stretching between 70° and 84° of north latitude (see Fig. 8). It is in reality two islands separated by a narrow strait near the latitude of 76°. The northern island, which to the north is a plateau attaining an altitude of 1,800 feet, appears to be in large part covered by inland-ice, though it has been as yet but little explored.

The Inland-ice of Spitzbergen.—The group of islands to which the name Spitzbergen has been applied, lies between the parallels of 76° and 81° of north latitude. The surface is generally mountainous, the highest peaks rising to an elevation of about 5,000 feet, though the greater number range from 2,000 to 4,000 feet in altitude. The large northeastern land mass is called North East Land and is covered with inland-ice which was crossed by Nordenskiöld and Palander in 1873[11] (see Fig. 9). New Friesland, or the northeastern portion of the main island, is also covered by inland-ice[12] (see Fig. 10). The southwestern margin of this inland-ice was

FIG. 10. Inland-ice of New Friesland as viewed from Hinloopen Strait (after Conway).

somewhat carefully mapped by Conway and Gregory in 1896,[13] and as this presents some interesting general features, it is reproduced in part in Fig. 11.

In addition to the lobes which push out upon the crest of the plateau, there is here an expansion laterally beyond the main cap and at lower levels in the form of an apron which is called the Ivory Gate (compare the Frederikshaab Glacier in Fig. 38, p. 119). Surrounding the inland-ice to the westward are small ice-caps resembling the fjelds and braes of Norway, and also true mountain glaciers whose cirques have shaped the mountains into the sharp pinnacles of comb ridges. It is to these sharp peaks that Spitzbergen owes its name.

[11] A. E. Nordenskiold, "Grönland" (authorized German edition), map on p. 141.

[12] W. Martin Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, Vol. 12, 1898, pp. 137–158.

[13] Sir Wm. Martin Conway, "The First Crossing of Spitzbergen," London, 1897, pp. 371, 2 maps.

In the year 1890 Gustav Nordenskiöld made a journey between Horn Sound and Bell Sound on the west coast, and found behind the sharp peaks bordering the coast an ice surface almost without crevasses or nunataks.[14] Upon the northwest coast no sharp peaks or comb-ridges are found, but there is a low plateau with deep, narrow valleys similar to the west coast of Norway where it

FIG. 11. Map of the southwestern margin of an extension of the inland-ice of New Friesland (after Conway).

reaches the sea near the North Cape. All the rock surfaces are glaciated.

The inland-ice of North East Land reaches the sea upon the southern and eastern coasts, but is surrounded by a hem of land upon the north and west. Over the surface of this ice Nordenskiöld

[14] O. Nordenskiöld, *l. c.*, p. 52.

observed that the snow does not melt even in midsummer, and that hence there were developed no lines of surface drainage. Of especial note were the great crevasses which ran generally in straight lines for long distances in parallel series, sometimes two interesting series being observed. More remarkable than these, however, were the so-called "canals," which also for the most part ran parallel to each other and in some cases were only 300 feet apart. These

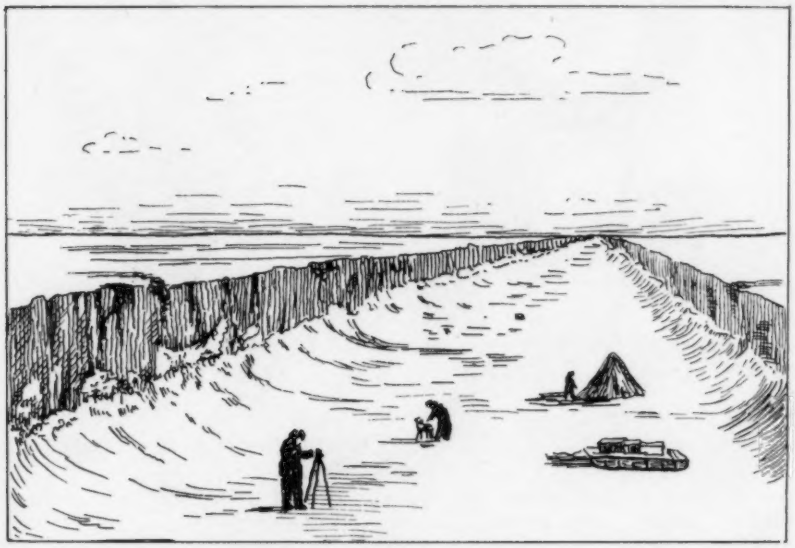

FIG. 12. Camping place in one of the "canals" upon the surface of the inland-ice of North East Land, Spitzbergen (after Nordenskiöld).

canals, which were found in the southeastern part of the area near Cape Mohn, were in reality deep, flat-bottomed troughs within the ice, bounded on either side by parallel and rectilinear ice cliffs, and were in places partially filled by the indrifted snow. Stretching for long distances over the snow plain, and set so deeply that they could be entered only where fortuitous drifting of the snow supplied an incline, they were utilized for camping places (see Fig. 12).

Nordenskiöld has explained these canals as trough faults within the ice, and has assumed that this deformation was due to changes

of volume incidental to extreme temperature range (see Fig. 13). This explanation in temperature changes would leave the absence of such structures in other places wholly unaccounted for, and we venture to believe that a recent trough faulting within the rock basement below the ice and communicated upward through it, would furnish a more reasonable assumption, particularly in view of our later knowledge of dislocations connected with earthquake disturbances.

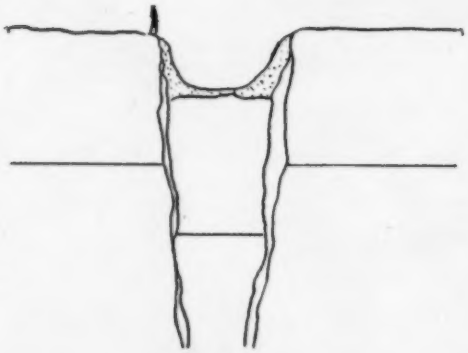

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FIG. 13. Hypothetical cross section of a glacial canal upon the inland-ice of North East Land (after Nordenskiöld).

FIG. 14. Map showing the supposed area of inland-ice upon Grinnell and Ellesmere Lands (from Andree's "Handatlas").

Still deeper in-breaks of the ice were encountered within the same region. These, though deeper, were generally of less extent, and were designated by the sailors of the party "docks" or "glacier docks."

The Inland-ice of Grinnell, Ellesmere and Baffin Lands.—Something has been learned of the inland-ice of Grinnell Land (see Fig. 14) from the report of Lieutenant Lockwood upon his crossing of Grinnell Land in 1883.[15] Of especial interest is his description of the ice front or face as it was observed for long distances

[15] A. W. Greely, "Report on the Proceedings of the United States Expedition to Lady Franklin Bay, Grinnell Land," Vol. 1, especially Appendix No. 86, pp. 274–279, pls. 1–4. See also Salisbury, Jour. Geol., Vol. 3, p. 890.

in the form of a perpendicular wall which he described under the name "Chinese Wall." Over upland and plain this wall extended with little apparent change in its character. At one place by pacing and sextant angle its height was estimated at 143 feet (see Fig. 15).

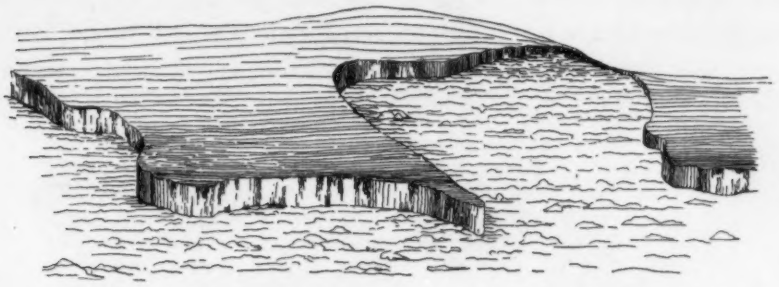

FIG. 15. View of the "Chinese Wall" surrounding the Agassiz Mer de Glace on Grinnell Land (after Greely).

The inland-ice of Ellesmere Land (see Fig 14) has been to some extent explored along its borders by members of the Sverdrup expedition. The maps of the margin in the vicinity of Buchanan Bay display much the same characters as may be observed along the margins of the better known ice-caps and inland-ice masses of the northern hemisphere.[16]

Of the inland-ice of Baffin Land little is known (see Fig. 16). There are some indications that a small ice-cap exists upon the neighboring island of North Devon.

PHYSIOGRAPHY OF THE CONTINENTAL GLACIER OF GREENLAND.

General Form and Outlines.—The inland-ice of Greenland, we have now good reason to believe, has the form of a flat dome, the highest surfaces of which lie somewhat to the eastward of the medial line of the continent,[17] and which envelops all but a relatively narrow marginal rim. This marginal ribbon of land is usually from five to twenty-five miles in width, may decrease to noth-

[16] Otto Sverdrup, "New Land," 2 vols., London, 1904, pp. 496–504.

[17] F. Nansen, "The First Crossing of Greenland," Vol. 2, p. 404; R. E. Peary, "Journeys in North Greenland," *Geogr. Jour.*, Vol. II., 1898, p. 232.

ing, but in two nearly opposite stretches of shore it widens to from sixty to one hundred miles (see Fig. 17).

At the heads of many deep fjords long and narrow marginal tongues pushing out from the central mass reach to below sea level; and within three limited stretches of shore the ice mantle overlaps the borders of the continent and reaches the sea in a broad front.

FIG. 16. Map showing the supposed area of inland-ice upon Baffin Land (from Andree's "Handatlas").

The longest of these begins near the Devil's Thumb on the west coast at about latitude 74′ 30″, and extends with some interruptions for about one hundred and fifty miles along the coast of Melville Bay.[18] Where crossed by Nansen near the parallel of 64°, and hence near the southern margin, and also where traversed by Peary near its northwestern borders, the inland-ice has revealed much

[18] T. C. Chamberlin, "Glacial Studies in Greenland," III., *Jour. Geol.*, Vol. 3, 1895, pp. 62–63.

the same features. The great central area has never been entered, although Baron Nordenskiöld and Lieutenant Peary, as well as Nansen, have each passed somewhat within the margin near the

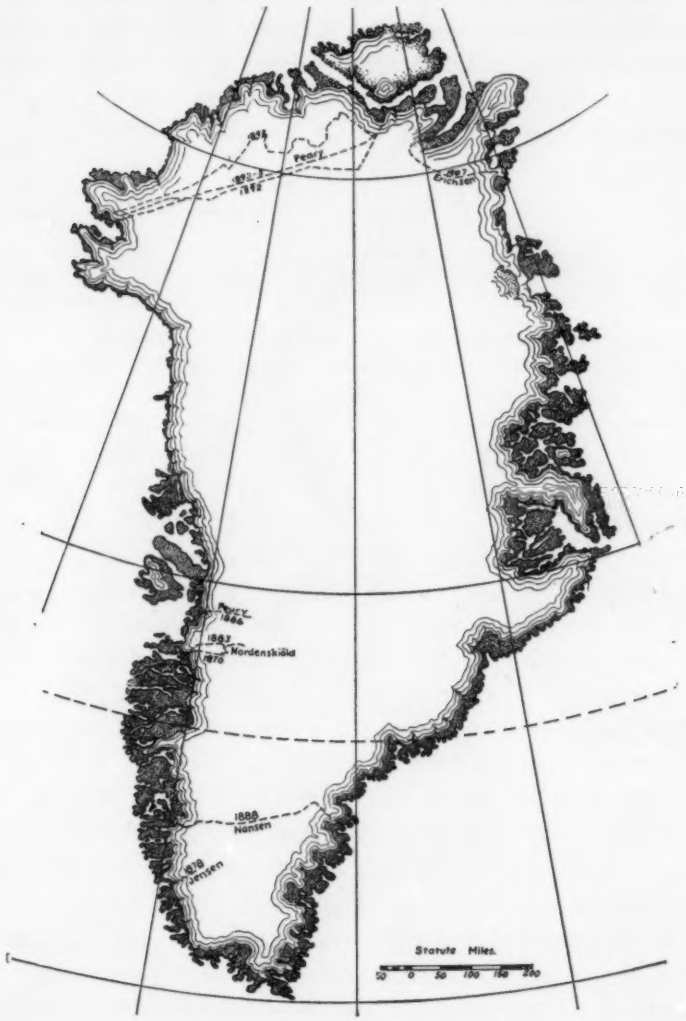

FIG. 17. Map of Greenland, showing the outlines of the inland-ice (from Andree's "Handatlas," but corrected for the northeast shore from data of the Danish expedition of 1908). The routes of the various expeditions on the inland-ice have also been added.

latitude of 68°. More recently (1907) Mylius Ericksen met his tragic death in crossing the inland-ice in northeast Greenland, but his results, most fortunately recovered, are not yet published. Yet such is the monotony of the surface thus far revealed, and such the uniformity of conditions encountered, that there is little reason to think future explorations in the interior will disclose anything but a desert of snow with such small variations from a horizontal surface as are not strikingly apparent to the traveller at any one observing point.

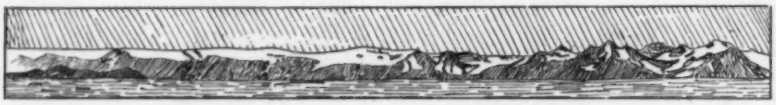

FIG. 18. Sketch of the east coast of Greenland near Cape Dan. Shows the inland-ice and the work of marginal mountain glaciers (after Nansen).

Nansen has laid stress upon the close adherence of the curve of his section to that of a circle, and has attempted to apply this interpretation to the sections of both Nordenskiöld and Peary made near the latitude of Disco Bay.[19] If the marginal portions of the sections be disregarded, this interpretation is possible for Nansen's own profile, since it is in any case very flat; but inasmuch as the margins only were traversed in the other sections, the conclusions drawn from them are likely to be misleading when extended into the unknown interior.

Hess,[20] correcting Nansen's data so as to take account of the curvature of the earth, finds the radius of this circle of the section to be approximately 3,700 km. (instead of 10,380 km., as given by Nansen). This radial distance being considerably less than the average for the earth's surface, the curvature of the ice surface where crossed by Nansen is considerably more convex than an average continental section.

We are absolutely without knowledge concerning either the thickness of the ice shield or the elevation of the rock basement

[19] H. Mohn und Fridtjof Nansen, "Wissenschaftlichen Ergebnisse von Dr. F. Nansens Durchquerung von Grönland, 1888," *Pet. Mitt. Ergänzungsh.*, 105, 1892, pp. 1–111, 6 pls., 10 figs. Especially Plate 5.

[20] "Die Gletscher," pp. 105–106.

beneath it; though a height of the snow surface of approximately 9,000 feet was reached by Nansen at a point where it could hardly be expected to be a maximum. The snow surface to the north of his section was everywhere rising, and it is likely that it attains an altitude to the northeastward well above 10,000 feet.

Though doubtless almost flat within its central portions, and only gently sloping outward at distances of from seventy-five to one hundred miles within its margin, the snow surface falls away so abruptly where it approaches its borders as to be often quite difficult of ascent (see Fig. 19).[21] The monotony of the flatly arched cen-

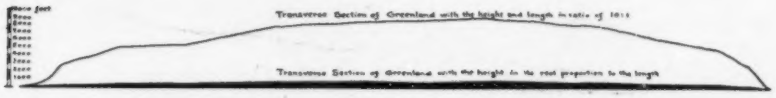

FIG. 19. The section across the inland-ice of Greenland, near the 64th parallel of latitude in natural proportions and with vertical scale ten times the horizontal (after Nansen).

tral portion of the isblink gives place to wholly different characters as the margins are approached. The ice descends in broad terraces or steps, which have treads of gentle inclination but whose risers are of greater steepness, and this steepness is rapidly accelerated as the margin is neared. In Fig. 20 have been placed together for comparison the profiles of Peary, Nordenskiöld and Nansen on the different routes which they travelled toward the interior from the coast.

The margins of the Greenland continent where uncovered by the ice, are generally mountainous, with heights reaching in many cases to between 5,000 and 8,000 feet on the east shore[22] and between 5,000 and 6,000 feet on the west shore. The bordering ice-caps within these areas are developed in special perfection on the islands of the archipelago about King Oscars fjord and Kaiser

[21] R. E. Peary, "A Reconnoissance of the Greenland Inland-ice," *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, pp. 261–289.

[22] Petermann Peak near Franz Josef fjord on the east coast, which according to Nansen has an estimated height of 11,000–14,000 feet, has recently been shown to be not more than half that height (A. G. Nathorst, *Pet. Mitt.*, Vol. 45, 1899, p. 242).

Franz Josef fjord on the east coast near latitude 75° N., as these have been mapped by the Swedish Greenland Expedition of 1899 (see Fig. 21).[23] The work of mountain glaciers about King Oscars fjord is clearly displayed by Nathorst's photograph reproduced in Plate XXVI, *A*. Essentially the same features are shown also to the right in Fig. 18 (p. 78).

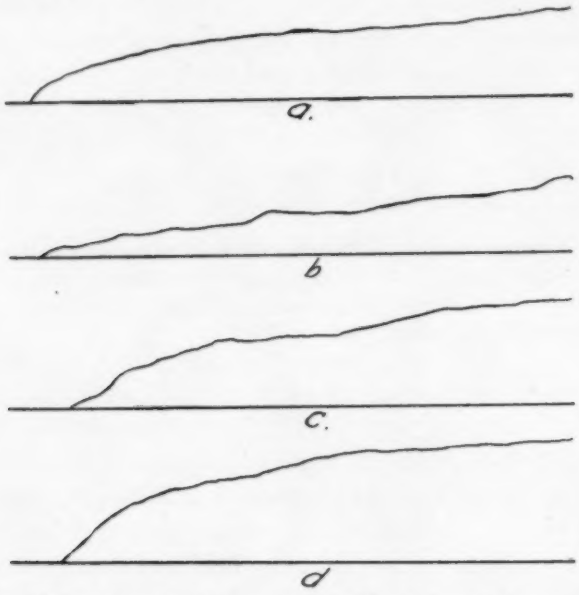

FIG. 20. Comparison of the several profiles across the margin of the inland-ice (*a*) at latitude 69 1/2° on the west coast (Peary); (*b*) at latitude 68 1/2° on the west coast (Nordenskiöld); (*c*) at latitude 64° on the west coast (Nansen); and (*d*) at latitude 64 1/2° on the east coast (Nansen).

While we are without absolute knowledge of the relief of the land beneath most of the inland-ice, we know that the mountainous upland of the coast extends well within the ice margins, since the peaks project through the surface as ice-bounded rock islands or *nunataks*. The irregularities of this basement and the submergence and consequent drowning of the valleys to form deep fjords within the marginal zones, largely account for the markedly lobate out-

[23] A. G. Nathorst, "Den svenska expeditionen till nordöstra Grönland," 1899, *Ymer*, Vol. 20, 1900, map 11.

lines of the so-called isblink[24] or inland-ice, as well as for the ice-caps and mountain glaciers, which originating in the outlying plateaus and mountains, form a fringe about the central ice mass.

It has been shown to be characteristic of the ice-caps and smaller inland-ice areas of the Arctic region outside of Greenland, that their lobate margins are in part accounted for by extensions of the

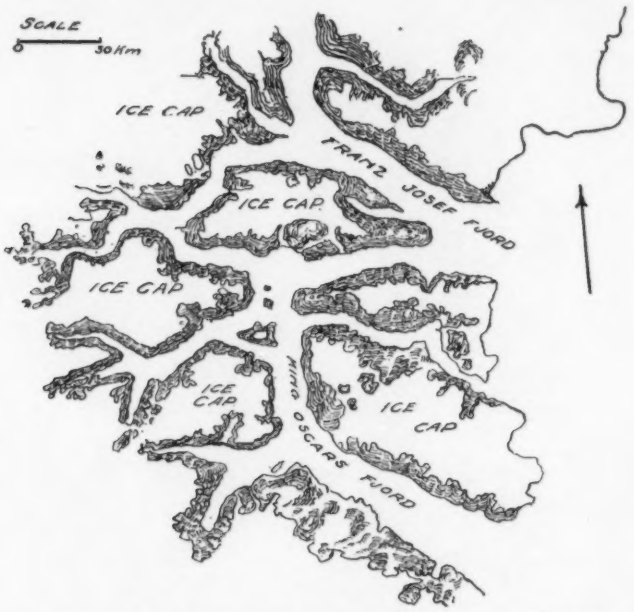

FIG. 21. Map of the region about King Oscars and Kaiser Franz Josef fjords, Eastern Greenland, showing the areas of the numerous ice-caps (after P. Dusen).

cap upon the plateau between intersecting valleys or fjords, as well as by extensions down these valleys. These latter extensions of the ice sheets are, however, much the narrower. Identically the same features are found to characterize the Greenland inland-ice as well. The manner in which this occurs in Greenland has been

[24] "Iceblink," which has been suggested by some writers, is a term generally applied among navigators to describe the appearance of ice on the horizon, and is contrasted with "land blink," which describes the peculiar loom of the land. In order to apply the term to the inland-ice without confusion, it is, therefore, better to retain the Danish form of the word.

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well brought out in a map and section by Helland[25] of the Kangerdlugsuak fjord and glacier, but even better by recent maps of the

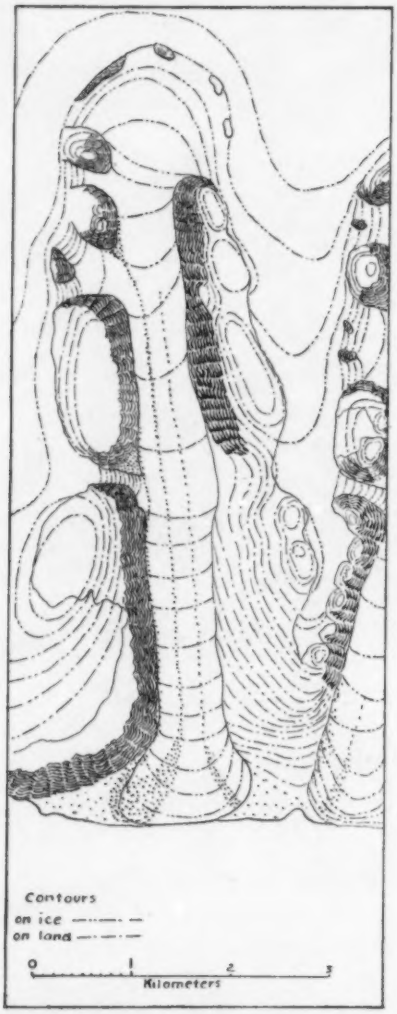


FIG. 22. Map of a glacier tongue, which extends from the inland-ice down the Umanak fjord (after von Drygalski).

[25] A. Helland, "On the Ice Fjords of North Greenland and on the Formation of Fjords, Lakes, and Cirques in Norway and Greenland," *Quart. Jour. Geol. Soc.*, Vol. 33, 1877, pp. 142–176.

Petermann Fjord by Peary (Fig. 25, p. 89) and the Umanak fjord by von Drygalski[26] (see Fig. 22). The manner in which the ice sometimes descends from the higher levels over the steep walls of the fjords has been strikingly brought out in a photograph of the Foetal glacier (see Fig. 23).[27]

As already stated, within one limited stretch upon the west coast the ice mantle overlaps the borders of the continent and reaches

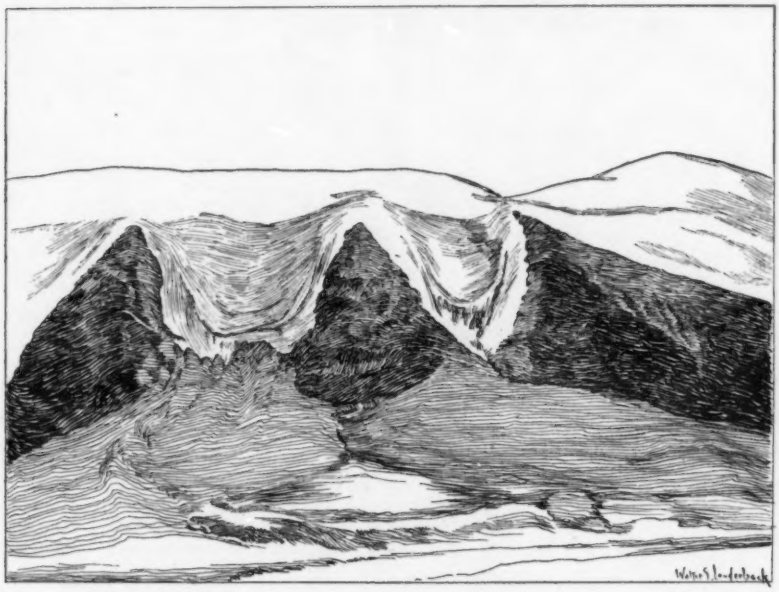


FIG. 23. Tongues of ice descending from the Foetal glacier, McCormick Bay (after Peary).

the sea in a broad front. This stretch of coast begins near the Devil's Thumb at about latitude 74° 30′ and extends, with some interruption, for about 150 miles along the coast of Melville Bay.[28] On the northeast coast the recent explorations of the Danes indicate that there are two stretches of 20 and 60 miles, respectively,

[26] E. von Drygalski, "Grönland-Expedition," Vol. 1, 1897, Map 7.

[27] R. E. Peary, "Journey in North Greenland," *Geogr. Jour.*, Vol. 11, 1898, pp. 213–240.

[28] T. C. Chamberlin, "Glacial Studies in Greenland, III.," *Jour. Geol.*, Vol. 3, 1895, p. 61.

within which the ice in like manner reaches the sea. These occur on Jökull Bay and on the north shore of the North East Foreland (see Fig. 24).[29]

The Ice Face or Front.—Concerning the form of the front of the inland-ice where it lies upon the land, widely different descriptions have been furnished from different districts. It is necessary

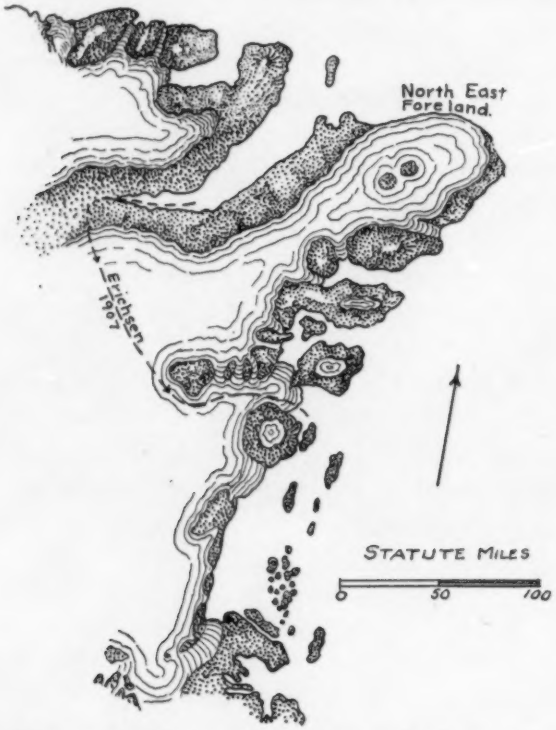


FIG. 24. Map of the Greenland shore in the vicinity of the North East Foreland (after Trolle).

to remember that the continent of Greenland stretches northward through nearly 24° of latitude, and after due regard is had to this consideration, the differences in configuration may perhaps be found to be but expressions of climatic variation. Those who have

[29] Lieut. A. Trolle, "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 57–70 (map and illustrations).

studied the land margin of the isblink in North Greenland, all call attention to the precipitous and generally vertical wall which forms the ice face (see Plate XXVI, *B*). As a result of shearing and overthrusting movements within the ice near its margin, as well as to the effect of greater melting about the rock fragments imbedded in the lower layers of the ice, the face sometimes even overhangs in a massive ice cornice at the summit of the wall (see Plate XXVII, *A*).[30]

That to this remarkable steepness of the ice face as observed north of Cape York there are exceptions, has been mentioned by both Chamberlin and Salisbury, but Peary has also emphasized the vertical face as a widely characteristic feature of North Greenland. The recent Danish expedition to the northeast coast of Greenland has likewise furnished examples of such vertical walls. An instance where the ice face appears as a beautifully jointed surface somewhat resembling the rectangular joint-walls in the quarry faces of certain compact limestones, is reproduced from the report of the expedition in Plate XXVII, *B*.[31]

Attention has already been called to the precipitous front, the so-called "Chinese Wall," which Lieutenant Lockwood found to form the land face of the inland-ice of Ellesmere Land—a face which was followed up and down over irregularities of the land surface, and whose height in one place was roughly measured as 143 feet (see Fig. 15, p. 75).

From central and southern Greenland, on the other hand, we hear little of such ice cliffs as have been described, and Tarr in studies about the margin of the Cornell extension of the isblink[32] has shown that here the vertical face is the exception.[33] The normal sloping face as there seen is represented in Plate XXVIII, *A*. In following the ice face for fifteen miles, its slopes were here found to be sufficiently moderate to permit of frequent and easy ascent

[30] Chamberlin, *Jour. Geol.*, Vol. 3, 1895, p. 566. Salisbury, *ibid.*, Vol. 4, 1896, p. 778.

[31] Gunnar Andersson, "Danmarks expeditionen till Grönlands nordostkust," *Ymer*, Vol. 28, 1908, pp. 225–239, maps and 7 figures.

[32] To the south of the upper Nugsuak Peninsula in latitude 70° 10′ N.

[33] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geologist*, Vol. 20, 1897, pp. 139–156, pls. 6–12.

and descent. Inasmuch as these sloping forms are characteristic of the ice front in the warmer zones, and further correspond to that generally characteristic of mountain glaciers in lower latitudes, it seems likely that its occurrence in Greenland is limited to districts where surface ablation plays a larger rôle.

In northeast Greenland (lat. 77°–82°) according to the Danes, "the frontier of the inland ice is in some places quite steep, in other places you might have mounted the inland ice without knowing it."

Features Within the Marginal Zone.—The larger terraces upon the ice slope, Nansen has ascribed to peculiarities of the rock floor on which the ice rests. Where the slopes become still more accelerated toward the margin of the ice, deep crevasses appear upon these steps running parallel to their extension, and hence parallel to the margins of the ice. Nansen found, however, that such crevasses were restricted to the outer seven or eight miles on the eastern side of his section, and to the outer twenty-five miles on its western margin. Peary in his reconnoissance across the ice border in latitude 69½°, saw such crevasses while they were opening and the surface snow was sinking into the cleft thus formed. The visible opening of the cleft was accompanied by peculiar muffled reports which rumbled away beneath the crust in every direction.[34] Of the terraced slope and its fading into the plateau above he says:

> The surface of the "ice-blink" near the margin is a succession of rounded hummocks, steepest and highest on their landward sides, which are sometimes precipitous. Farther in these hummocks merge into long, flat swells, which in turn decrease in height towards the interior, until at last a flat gently rising plain is revealed which doubtless becomes ultimately level.[35]

In sketching the general form of the Greenland continental glacier, it has been stated that the highest portion of the shield lies to the eastward of the medial line of the continent. This is shown by Nansen's section, and is emphasized by Peary, who says:

> That the crest of the Greenland continental ice divide is east of the country's median line there can be no doubt.[36]

[34] *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, p. 277.
[35] *Geogr. Jour.*, Vol. 11, 1898, pp. 217, 218.
[36] *Geogr. Jour., l. c.*, p. 232.

By von Drygalski[37] this lack of symmetry of the ice material has been ascribed to excessive nourishment upon the east, whereas the losses from melting and from the discharge of bergs occur mainly upon the west. The mountains of the east are, he states, completely surrounded by ice so that peaks alone project, while the mountains of the west stand isolated from the ice. In attempting to make the eccentric position of the boss in the ice shield depend upon the configuration of the underlying rock surface, von Drygalski has been less convincing, for we know that the Scandinavian continental glacier of Pleistocene times moved northwestward from the highest surface of the ice-shield up the grade of the rock floor, and pushed out through portals in the mountain barrier which lies along the common boundary of Sweden and Norway. Still there would appear to be a clear parallel between the marginal terraces of the inland-ice with their crevassed steep surfaces, and the plateaus and ice falls which alternate upon the slopes of every mountain glacier which descends rapidly in its valley.

Superimposed upon the flats of the larger ice terraces, there are undulations of a secondary order of magnitude, and these Nansen ascribed to the drifting of snow by the wind. To the important action of wind in moulding the surface of the inland-ice we shall refer again. There are in addition many other irregularities of the surface due to differential melting, and while of very great interest, their consideration may profitably be deferred until the meteorological conditions of the region have been discussed. There are, however, other features which like the broader terraces are clearly independent of meteorological conditions, and which are, therefore, best considered in this connection.

Dimples or Basins of Exudation Above the Marginal Tongues. —Seen from the sea in Melville Bay on the northwest coast, the inland-ice offers special advantages for observing its contours in sections parallel to its front, that is to say, in front elevation. Here only upon the west coast the ice extends beyond the borders of the land and is cut back by the sea to form cliffs. These ice cliffs are

[37] E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.

interrupted by rocky promontories which are surrounded on all sides but the front by ice, and hence in reality the cliff furnishes us with sections through nunataks and inland-ice alike. Says Chamberlin:[38]

> Only a few of the promontories of the coast rise high enough to be projected across this sky line and interrupt the otherwise continuous stretch of the glacial horizon. The ice does not meet the sky in a simple straight line. It undulates gently, indicating some notable departure of the upper surface of the ice tract from a plane. As the ice-field slopes down from the interior to the border of the bay, it takes on a still more pronounced undulatory surface. It is not unlike some of our gracefully rolling prairies as they descend from uplands to valleys, when near their middle-life development.

The two 1,200-mile sledge journeys of Peary in the years 1891–92, and 1893–95 across the northern margin of the "Great Ice" of Greenland, have added much to our knowledge of the physiography of the inland-ice. These journeys were made on nearly parallel lines at different distances from the ice border, and so, if studied in relation to each other, they display to advantage the configuration of the ice surface near its margin (see Fig. 25). The routes were for the most part nearly straight and ran at nearly uniform elevations which ranged from 5,000 to 8,000 feet above the sea.[39] In the sections nearest the coast, however, the route at first ascended a gentle rise to a flatly domed crest upon the ice only to descend subsequently into a broad swale of the surface, the bottom of which might be described as a plateau, and which was continued in the direction of the coast by a tongue-like extension of the ice, such as the tongue in Petermann Fjord between Hall Land and Washington Land (Fig. 25). On the further side of this basin-like depression, the surface again rose until another domed crest had been reached, after which a descent began into a swale similar to the first. On the return journey by keeping farther from the ice margin these elongated dimples upon the ice surface were avoided. The broad domed surfaces which separate the dimples clearly lie over the land ridges between the valleys down which the glacier tongues descend toward the sea.

[38] "Glacial Studies in Greenland, III.," *Jour. Geol.*, Vol. 3, 1895, p. 63.

[39] *Geogr. Jour.*, Vol. 11, 1898, p. 215. See also his map, *Bull. Am. Geogr. Soc.*, Vol. 35, 1903, p. 496.

FIG. 25. Map showing routes of sledge journeys in North Greenland in their relation to the margin of the ice (after Peary).

Peary has referred to these dimples on the surface of the inland-ice as "*basins of exudation,*" and has compared the cross profile in its ups and downs to that of a railroad located along the foothills of a mountain system.[40] In his earlier reconnaissance of the isblink from near Disco Bay, Peary describes such a dimple above the Jakobshavn ice tongue "stretching eastward into the 'ice-blink,' like a great bay," as a *feeder basin.*[41] The exact form of such dimples upon the ice surface is well brought out in von Drygalski's map of the Asakak glacier tongue on the Umanak Fjord (see Fig. 22, p. 82).[42]

We may easily account for the existence of these dimples by drawing a parallel from the behavior of water as it is being discharged from a lake through a narrow and steeply inclined channel. Under these circumstances the surface is depressed through the indrawing of the water on all sides to supply the demands of the outflowing current. That within the upper portions of the glacier tongues of the Greenland isblink the ice flows with a quite extraordinary velocity has long been known. Values as high as 100 feet per day have been determined upon the Upernavik glacier.[42a] By more accurate methods, von Drygalski has obtained on one of the ice tongues which descends to a fjord, a rate of about 18 meters or 59 feet in twenty-four hours.[43] Upon the inland-ice some distance back from the head of the fjord, on the other hand, a rate was measured of only one to two centimeters per day.

Scape Colks and Surface Moraines.—The velocities of ice movement which obtain within and about the heads of the glacial tongues are, there is thus every reason to believe, as different as possible from the ordinary general outward movement of the inland-ice. Within this marginal zone areas of exceptional velocity of the inland-ice are likely to be found wherever its progress is interfered with by the projecting nunataks. Just as jetties by constricting

[40] *Geogr. Jour.*, Vol. 11, p. 232.

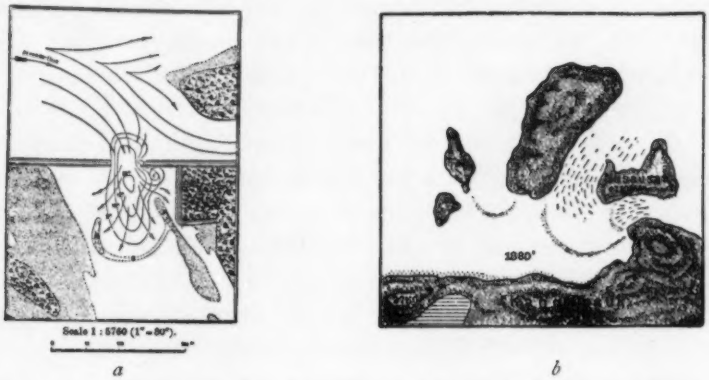
[41] *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, p. 269.

[42] "Grönland-Expedition," *l. c.*, map 7.

[42a] Lieut. C. Ryder in 1886. Helland on a glacier of the Jakobshavnfjord found a rate of 64 feet daily.

[43] E. von Drygalski, "Die Bewegung des antarktischen Inlandeises," *Zeitsch. f. Gletscherk*, Vol. 1, 1906–7, pp. 61–65.

the channels greatly accelerate the velocity of stream flow within those channels, so here within the space between neighboring nunataks a local high rate of flow in the ice is developed. An inevitable and quite important consequence of this constriction was long ago pointed out by Suess and illustrated by the area between Dalager's Nunataks near the southwestern border of the isblink.[44] Here again the conduct of water which is being discharged through narrow outlets has supplied both the illustration and the explanation. In the regulation of the flow of the Danube below Vienna, the river was partially closed by a dam, the Neu-Haufen dyke, and the floor in the channel below the dike was paved with heavy stone



a *b*

FIG. 26. *a*, Closure of the Neu-Hauen dyke, Schüttau in the regulation of the Danube below Vienna (after Taussig); *b*, scape colks near Dalager's Nunataks (after Jensen and Kornerup).

blocks. The effect of thus narrowing the channel of the river was to raise the level of the water above the dike by almost a meter, and under this increased head the current tore out the heavy stone paving of the floor of the channel and dug a depression above as well as below the outlet. This excavation by the current represented a hole dug to a depth of about fifteen meters. The blocks which had been torn out from the pavement were left in a crescent-shaped border to the depression upon its downstream side (see Fig. 26, *a*).

[44] Ed. Suess, "Face of the Earth," Vol. 2, 1888 (translation, 1906), pp. 342–344.

The position of a surface moraine which stretches in a sweeping arc from the lower edge of one of Dalager's Nunataks to a similar point upon its neighbor, indicates a complete parallel between the motion of the ice and the water at the Neu-Haufen dyke, the rock débris of the deeper ice layers being here brought up to the surface. Study of the Scandinavian inland-ice of late Pleistocene times throws additional light upon the nature of this process. Flowing from a central boss near the head of the Gulf of Bothnia, the ice pushed westward and escaped through narrow portals in the escarpment which now follows the international boundary of Sweden and Norway. This constriction of its current has been appealed to by Suess to account for the interesting glint lakes which to-day lie across this barrier and extend both above and below the former outlets of the ice.[45] Lakes which have this origin he has described under the term scape colks. Perhaps if examined more carefully we should find that the bringing up of the englacial débris to the surface of the ice, is only partially due to the inertia of motion in the ice. With the more rapid flow of the ice within the constricted portion, the basic portions, shod as they are with rock fragments, accomplish excessive abrasion upon the rock bed. This is in accord with Penck's law of adjusted cross sections in glacial erosion. Where the ice channel broadens below the nunataks, the abrasion again becomes normal so that a wall develops at this place in the course of the stream.

Here, therefore, a new process comes into play due to the peculiar properties of the plastic ice, a process which has been illustrated in the formation of drumlins beneath former continental glaciers, and has been given an experimental verification. Case has shown that paraffin mixed with proper proportions of refined petroleum, and maintained at suitable temperatures, can be forced by means of plungers[46] through narrow boxes open at both ends. It was shown in the experiments that an obstruction interposed at the bottom and in the path of the moving paraffin, forced the bottom layers upward, and this upward movement continued beyond

[45] Suess, *l. c.*, pp. 337–346.

[46] E. C. Case, "Experiments in Ice Motion," *Jour. Geol.*, Vol. 3, 1895, pp. 918–934.

the position of the obstruction. The experiments of Hess[47] give results which are consistent with those of Case. Hess employed in his experiments parallel wax disks of alternating red and white colors, and these were forced under hydraulic pressure through a small opening. It was found that the layers turn up to the surface in this "model glacier" apparently as a result of the friction upon the bottom and at only moderate distances from the opening where the energy of the active moving substance pressing from the rear has to some extent been dissipated.

In Chamberlin's studies of certain Greenland glaciers, he was permitted to observe the effect upon the motion of the glacier of low prominences in its bed. These observations are confirmatory of the experiments described.[48]

The swirl colks or eddies which Suess has suggested as occurring below nunataks, in order to account for certain lakes in Norway, seemed to be much less clear, and it is a little difficult to assume an eddy in the ice which is in any way comparable to the eddies of water.

Marginal Moraines.—Inasmuch as the rock appears above the surface of the ice of the Greenland continental glacier only in the vicinity of its margins, and here only as small islands or nunataks, the rock débris carried by the Greenland ice must be derived almost solely from its basement. As described in detail by Chamberlin, it is the lower 100 feet of ice to which englacial débris is largely restricted.[49] Medial moraines, if the term may be properly applied to those ridges of rock débris which upon the surface of the ice go out from the lower angles of nunataks, have been frequently described by Nansen and others. They seem to differ but little from certain of the medial moraines which have been described in connection with the larger mountain glaciers.

Nansen has mentioned heavy terminal moraines in the Austmann Valley where he came down from the inland-ice after crossing the

[47] "Die Gletscher," 1904, p. 171, fig. 28.

[48] "Recent Glacial Studies in Greenland." Annual address of the President of the Geological Society of America, *Bull. Geol. Soc. Am.*, Vol. 6, 1895, pp. 199–220, pls. 3–10.

[49] Chamberlin, *l. c.*, p. 205.

continent. The material of these moraines consisted mainly of rounded and polished rock fragments, and is obviously englacial material.[50] Along the land margin of the Cornell ice tongue Tarr found a nearly continuous morainic ridge parallel to the ice front. This ridge usually rests at the base of the ice foot, and is sometimes a part of this foot, wherever débris has accumulated and protected the ice beneath from the warmth of the sun. Such an accumulation causes this part of the glacier to rise as a ridge. In other cases the ridge is, however, separated from the ice margin, and sometimes there are several parallel ridges from which the ice front has successively withdrawn[51] (see Plate XXVIII, *B*).

According to von Drygalski the marginal moraines of the Greenland ice sheet as regards their occurrence, form, and composition, are in every way like those remaining in northern Europe from the time of the Pleistocene glaciation, and this is true of those which run along the present border of the inland-ice as well as of those still mightier ancient moraines which follow at certain distances.[52] These moraines are generally closely packed blocks with relatively slight admixture of finer material. They are the largest where the ice border enters the plains, or pushes out upon a gentle slope, and they are smallest where the ice passes steep rocky angles.

It is worthy of note that the marginal moraines of Greenland become locally so compact and resistant that they oppose a firm obstruction to the ice movement. Then the ice pushes out laterally into the marginal lakes which develop there or pushes up upon the moraines. It thus comes to arrange its layers parallel to the slope of the morainic surface or, in other words, so that they dip toward the ice.[53]

Another type of marginal moraine which was mentioned by Mohn and Nansen from south Greenland, and later fully described by Chamberlin from north Greenland, is explained by the upturn-

[50] Mohn u. Nansen, "Wissenschaftlichen Ergebnisse von Dr. F. Nansen's Durchquerung von Grönland, 1888," *Pet. Mitt. Ergänzungsb.*, 105, 1892, p. 91.

[51] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geol.*, Vol. 20, 1897, p. 148.

[52] Grönland-Expedition, *l. c.*

[53] von Drygalski, *l. c.*, p. 529.

ing effect of obstructions in the bed, and by the shearing and overthrusting movements which are found to exist in inland-ice near its margin[54] (see Figs. 27 and 28). This process has much in

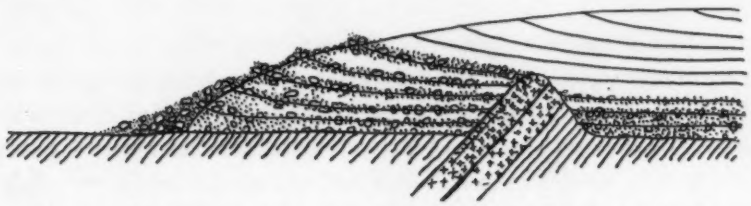


FIG. 27. Diagram to show the effect of a basal obstruction in the path of the ice near its margin (after Chamberlin).

common with that which we have already described in connection with scape colks.

Fluvio-glacial Deposits.—Where studied by Chamberlin near Inglefield Gulf, there appears to be little or no gushing of water from beneath the inland-ice. Small streamlets only appeared be-

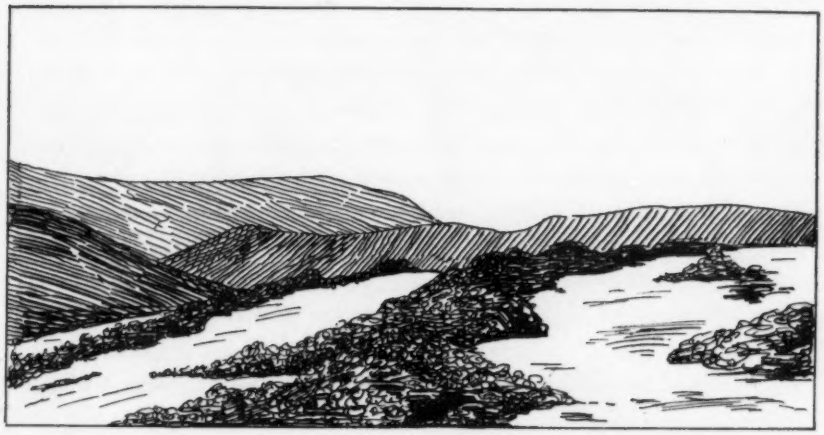


FIG. 28. Surface marginal moraine of the inland ice of Greenland.

neath the ice border, bringing gravel and sand which they distributed among the coarser morainic material. So far as land has been recently uncovered by the ice in north Greenland, and so far as differentiated from the topography of the underlying rock, it was

[54] Chamberlin, *l. c.*, p. 92.

found to be nearly plane. So far as known, no eskers have been observed about the border of the inland-ice of Greenland and only a few irregular kames near Olrik's Bay.[55]

Nourishment of the Greenland Inland-ice.

Few and Inexact Data.—The problems involving the gains and the losses of the inland-ice of Greenland require for their satisfactory solution a much larger body of exact data than we now possess. Barring a few scattered and not always exact or reliable observations, we are practically without knowledge of the amount or the variations of atmospheric pressure, or of snowfall away from the coastal areas of the continent. Even within these marginal zones, the losses from ablation and through the calving of bergs have been estimated by crude methods only. Again, the great height of the ice surface within the central plateau, and the lack of any knowledge of the elevation of the land surface in those regions, has raised questions concerning the conditions of flow and of fusion upon the bottom, which will probably long remain subjects of controversy.

An international coöperative undertaking with one or more stations established in the interior at points where altitude has been determined by other than barometric methods, and with coast stations maintained contemporaneously and for a period of at least a year, particularly if they could be supplemented by balloon or kite observations, would yield results of the very greatest importance.[56] The Greenland ice having shrunk greatly since the Pleistocene period, it is almost certain that its alimentation to-day does not equal the losses which it suffers along its margins—which in but slightly altered form applies to the Antarctic continental glacier as well.

Snowfall in the Interior of Greenland.—Almost the only data upon this subject are derived from a rough section of the surface layers of snow, as this was determined by Nansen with the use of

[55] Salisbury, *l. c.*, p. 809.

[56] Robert Stein, "Suggestion of a Scientific Expedition to the center of Greenland," Congrés Intern. pour l'Étude des Regions Polaires, Brussels, 1906, pp. 1–4 (separate).

a staff near the highest point in his journey across the inland-ice along the 64th parallel. At elevations in excess of 2,270 meters Nansen found the surface snow "soft" and freshly fallen, but of dust-like fineness. Beneath the surface layer, a few inches in thickness only, there was a crust less than an inch in thickness which was ascribed to the slight melting of the surface in midsummer,[56a] and below this crust other layers of the fine "frost snow" more and more compact in the lower portions, but reaching a thickness of fifteen inches or thereabouts before another crust and layer was encountered.[57] Other sections made in like manner by pushing down a staff, revealed similar stratification of the surface snow with individual layers never exceeding in thickness a few feet. From these observations Nansen has drawn the conclusion that the layers of his sections correspond to seasonal snowfalls, the thin crust upon the surface of each being due to surface melting in the few warm days of midsummer. He cites Nordenskiöld as believing that the moist winds which reach the continent of Greenland deposit most of their moisture near the margin.[58]

The sky during almost the entire time of the journey is described by Nansen as so very clear that the sun could be seen, and there were few days in which the sky was completely overcast. Even when snow was falling, which often happened, the falling snow was not thick enough to prevent the sun showing through. This clearly indicates that the snow falls from layers of air very near the snow surface below. The particles which fell were always fine, like frozen mist—what in certain parts of Norway is known as "frost snow"; that is, snow which falls without the moisture first passing through the cloud stage.[59]

The air temperatures even in August and September, when the crossing was made, were on the highest levels seldom much above the zero of the Fahrenheit scale, and at night they sank by over 40° F. (in one case to — 50° F.).

[56a] In the light of later studies this may as satisfactorily be explained through hardening by the wind.

[57] Mohn u. Nansen, *l. c.*, p. 86.

[58] Nansen, *l. c.*, Vol. 1, p. 495.

[59] Nansen, *l. c.*, Vol. 2, p. 56.

PROC. AMER. PHIL. SOC., XLIX, 194 G, PRINTED JUNE 9, 1910.

Peary, while on the inland-ice in north Greenland in the month of March, 1894, registered on his thermograph a temperature of —66° F. and several of his dogs were frozen as they slept.[60] The high altitudes and the general absence of thick clouds over the inland-ice, permit rapid radiation, so that cold snow wastes and hot sand deserts have in common the property of wide diurnal ranges of temperature. The poverty of the air over the inland-ice in its content of carbon dioxide, as shown by the analysis of samples collected by Nansen, must greatly facilitate this daily temperature change.[61]

From studies in the Antarctic it is now known that most of the snow falls there in the summer season, and that little, if any, moisture can reach the interior from surface winds. The same is probably true also of the interior of Greenland.

Though the absolute humidity of the air upon the ice plateau of Greenland is always low, the relative humidity is large, and never below 73 per cent. of saturation in the levels above 1,000 meters. Evaporation occurs chiefly when the sun is relatively high, and when the air is again chilled the abstracted moisture is returned to the surface in the form of the almost daily snow mists or frost snow. The observations went to show that only in the warmest days of summer do the sun's rays succeed in melting a very thin surface layer of the snow. Of the thirty days that Nansen's party was at altitudes in excess of 1,000 meters, on only six is a definite snowfall reported. Within the interior of Greenland it appears that *no snow whatever is permanently lost from the surface by melting*.[62]

While the relative humidity of the air over the central plateau is so high, the absolute humidity is extremely low, being measured from 1.4 mm. to 4 mm., though generally much below the maximum value. The average absolute humidity was 2.5 mm. while the average relative humidity was 92 per cent.[63]

It has been claimed by v. Drygalski that the eastern portion of

[60] *Geogr. Jour.*, Vol. 11, 1898, p. 228.
[61] Mohn u. Nansen, *l. c.*, pp. 109–111.
[62] Nansen, *l. c.*, Vol. 2, p. 491. See also Peary, *Geogr. Journ.*, *l. c.*, p. 214.
[63] Mohn u. Nansen, *l. c.*, pp. 44–45.

the Greenland ice sheet is a great nourishing region, while the western slope, on the other hand, is the locus of excessive melting and discharge. In support of this view he adduces chiefly the admitted lack of symmetry of the ice mass.[64] So far as alimentation is concerned, the view does not seem to be as yet supported by any observations, and it can hardly be regarded as a tenable hypothesis.

The Circulation of Air over the Isblink.—No exact data upon atmospheric pressures are as yet available except from stations near the sea level, mainly along the western and northern coasts. Until stations have been maintained for a more or less protracted period within the interior of Greenland, none can be expected. None the less, upon the basis of the observed winds in those portions of Greenland which have been traversed, it may be safely asserted that a fixed area of high atmospheric pressure is centered over the Greenland isblink, and that the cold surface of this mass of ice is directly responsible for its location there. Nansen, as early as 1890, announced this fact, having observed "that the winds which prevail on the coasts have an especial tendency to blow outwards at all points."[65] After many years of experience in different portions of Greenland, Peary stated the law of air circulation above the continent in clear and forceful language:[66]

> Except during atmospheric disturbances of exceptional magnitude, which cause storms to sweep across the country against all ordinary rules, the direction of the wind of the "Great Ice" of Greenland is invariably radial from the center outward, normal to the nearest part of the coast-land ribbon. So steady is this wind and so closely does it adhere to this normal course, that I can liken it only to the flow of a sheet of water descending the slopes from the central interior to the coast. The direction of the nearest land is always easily determinable in this way. The neighborhood of great fjords is always indicated by a change in the wind's direction; and the crossing of a divide, by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer.

Except for light sea breezes blowing on to the land in February,

[64] E. v. Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64. See also by the same author, "Grönland-Expedition, etc.," pp. 533–539.

[65] Nansen, *l. c.*, Vol. 2, p. 496. Also Mohn and Nansen, *l. c.*, pp. 44–47.

[66] "Journeys in North Greenland," *Geogr. Jour.*, Vol. 11, 1898, pp. 233–234. See also "Northward over the 'Great Ice,'" Vol. 1, pp. lxix–lxx.

the Danish northeast Greenland expedition found "the wind was constantly from the northwest, this being the result of the high pressure of air which is found over the inland ice."[67]

These conditions of circulation are schematically represented in Fig. 29. In March, 1894, Peary encountered on the north slope

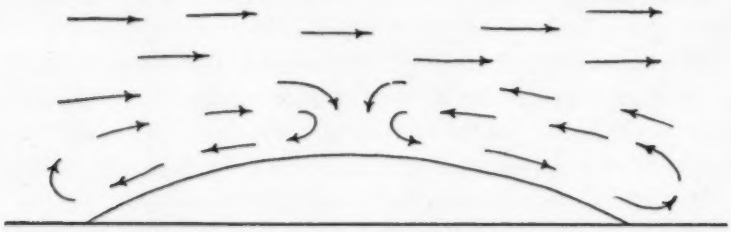


FIG. 29. Diagram to illustrate the air circulation over the isblink of Greenland.

of the inland-ice a series of blizzards before unprecedented in Arctic work, one lasting for three days, during which for a period of 34 hours the average wind velocity, as recorded by anemometer, was 48 miles per hour. Viewed in the light of violent southerly blizzards which Shackelton found to prevail upon the ice plateau in the Antarctic, these winds must be considered as belonging to the same Greenland or isblink system which has been described as of such general prevalence.

After comparing the meteorological data from his journey with contemporaneous observations on the shores of Baffin's Bay, Nansen believed that he was able to make out faintly the influence of general cyclonic movements. He says.[68]

> The plateau seems to be too high and the air too cold to allow depressions or storm centres to pass across, though, nevertheless, our observations show that in several instances the depressions of Baffin's Bay, Davis' Strait and Denmark Strait can make themselves felt in the interior.

Commenting upon Peary's conclusions above quoted, Chamberlin[69] ascribes the wind which flows downward and outward from

[67] Lieut. A. Trolle, R. D. N., "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 57–70 (map and illustrations).

[68] Nansen, *l. c.*, Vol. 2, p. 496.

[69] *Jour. Geol.*, Vol. 3, 1895, pp. 578–579.

the isblink to a notable increase of its specific gravity through contact with and consequent cooling by the snow surface.[70]

Foehn Winds Within the Coastal Belt.—The sliding down of masses of heavy air upon the snow surface of the Greenland ice must bring about adiabatic heating of the air and a consequent elevation of the dew point. The increase of temperature being about 1° C. for every 100 meters of descent, a rise of temperature of as much as 20° C. or 36° F. will result in a descent from the summit of the plateau, assuming this to have an elevation of 10,000 feet. Some reduction in the amount of this change of temperature will, of course, result from the contact of the air with the cold snow surface during its descent, this modification being obviously dependent upon the velocity of the current. The warm, dry winds which in different districts have been described under the names *foehn* and *chinook* are the inevitable consequence of such conditions, and are, moreover particularly characteristic of steep mountain slopes more or less covered by glaciers. Such foehn winds have long been recognized as especially characteristic of western Greenland. Dr. Henry Rink, who was a pioneer in the scientific study of Greenland, wrote in 1877:[71]

> Among the *prevailing winds* in Greenland the *warm land wind* is the most remarkable. Its direction varies according to locality from true E.S.E. to E.N.E. always proceeding though warm from the ice-covered interior, and generally following the direction of the fjord. It blows as frequently and as violently in the north as in the south, but more especially at the fjord heads, while at the same time in certain localities it is scarcely perceptible. It often turns into a sudden gale; the squalls in some fjords rushing down between the high rocks, in certain spots often sweep the surface of the water with the force of a hurricane, raising columns of fog, while the surrounding surface of the sea remains smooth.

[70] Professor v. Drygalski has shown that in the Great Karajak glacier near the coast in central western Greenland, the temperature of the snow and ice down to a depth of 60 feet or more undergoes a fall of temperature in response to the severity of the winter's cold, but in time this fall in temperature lags behind the period of maximum cold. Below that depth, however, it approximates in temperature to the zero of the centigrade scale. Temperatures of the snow measured just below the surface, varied from —11° to —26° C. (E. von Drygalski, "Grönland-Expedition der Gesellschaft für Erdkunde zu Berlin," 1891–1893, Vol. 1, 1897, pp. 470–472.)

[71] Henry Rink, "Danish Greenland, Its People and Its Products," London, 1877, p. 468.

Nansen encountered one of these foehn winds on his descent, and Peary mentions their occurrence in the north. In Scoresby's Land on the east coast, a foehn wind in the winter season has been known in a single hour to change the temperature by 24° C. (or 43° F.), and the maximum change during such a wind is far greater. It would not appear from observations that the winds of the Greenland system extend to any great distance above the surface, where the broad cyclonic areas in the atmosphere may be presumed to continue their courses with but slight modification. The anti-cyclone of the continent is, however, none the less clear and constant and is centered over the high interior. Nansen has remarked the calms over the divide of his section.[72]

There is some evidence that in adopting the important modern laws of adiabatic cooling of the air, we have allowed the pendulum to swing too far and have given too little weight to the effect of cooling through contact of air with either rock or snow. The latest results of Antarctic expeditions furnish the most striking proof of this, if other than Greenland examples were needed, and the Antarctic studies throw much light upon the conditions of snow distribution which are observed in Greenland.

Wind Transportation of Snow Over the Desert of Inland-ice.—Whymper and Nordenskiöld called Greenland a "Northern Sahara." In different ways Nansen and Peary have each instituted comparisons between the wastes of snow in the interior of Greenland and the desert of sand of the Sahara. The Norwegian explorer has emphasized especially the wide daily ranges of temperature, which because of generally cloudless atmospheres, both deserts have in common. Of the monotonous and elemental simplicity of the snow vistas back from the ice margin in North Greenland, Peary says:[73]

> It is an Arctic Sahara, in comparison with which the African Sahara is insignificant. For on this frozen Sahara of inner Greenland occurs no form of life, animal or vegetable; no fragment of rock, no grain of sand is visible. The traveller across its frozen wastes, travelling as I have week after week, sees outside himself and his own party but three things in all the world, namely, the infinite expanse of the frozen plain, the infinite dome of the cold blue sky, and the cold white sun—nothing but these (see Fig. 30).

[72] Nansen, *l. c.*, Vol. 2, pp. 487–488, 496.
[73] *Geogr. Journ., l. c.*, pp. 214, 215.

There is, however, yet another marked parallel between the snow waste and the sand desert. It is the importance of wind as a transporting agent. In his shorter acquaintance with southern Greenland Nansen was less impressed with this, but he has explained the secondary snow ridges upon the marginal terraces of the inland-ice as wind accumulations.[74] These long parallel ranges of snow drift thus correspond to the similar ranges of sand dunes

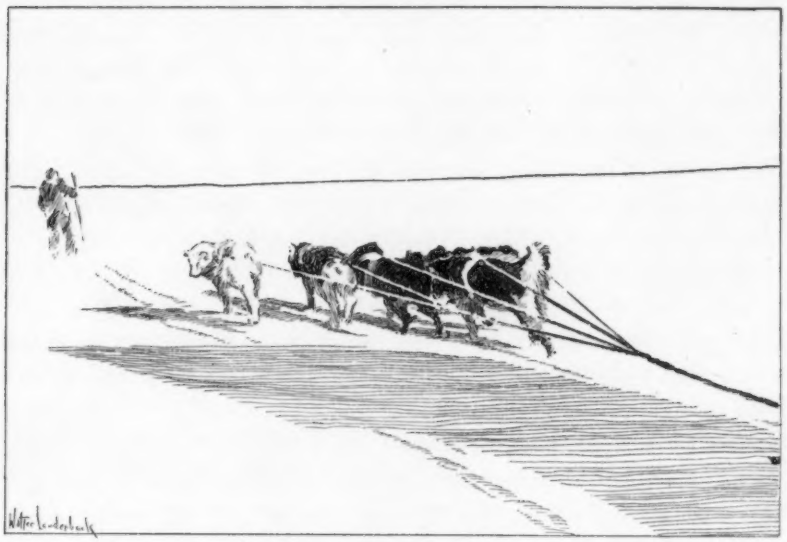


FIG. 30. On the Sahara of Snow (after Peary).

which sometimes throughout a width of many miles hem in the deserts of lower latitudes. In northern Greenland Peary's observations have a special value. He says:[75]

> There is one thing of especial interest to the glacialist—the transportation of snow on the ice-cap by the wind. . . .
>
> The opinion has been forced upon me that the wind, with its transporting effect upon the loose snow of the ice-cap, must be counted as one of the most potent factors in preventing the increase in height of the ice-cap—a factor equal perhaps to the combined effects of evaporation, littoral and subglacial melting, and glacial discharge. I have walked for days in an incessant sibilant drift of flying snow, rising to the height of the knees,

[74] Mohn u. Nansen, *l. c.*, p. 78.

[75] *Geogr. Jour., l. c.*, pp. 233–234.

sometimes to the height of the head. If the wind becomes a gale, the air will be thick with the blinding drift to the height of 100 feet or more. I have seen in the autumn storms in this region round an amphitheatre of some 15 miles, snow pouring down in a way that reminds one of Niagara. When it is remembered that this flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap, to the ice-free land at every foot of the periphery of the ice-cap, it will perhaps be seen that the above assumption is not excessive. I feel confident that an investigation of the actual amount of this transfer of snow by the wind is well worth the attention of all glacialists.

Fringing Glaciers Formed from Wind Drift.—In the vicinity of Inglefield Gulf in northwest Greenland, the inland-ice ends in a steep, snowy slope rising to a height of about 100 feet, where is a terminal moraine, above which moraine rises the great dome of the inland-ice. The whiteness and freshness of a portion of the snow of the outer border, when examined by Chamberlin,[76] showed it to be wind drift of recent accumulation. Locally, however, older and discolored snow appeared beneath the whiter surface snow, and in a few places stratified granular ice with some included rock débris. This snow and ice becomes augmented from year to year and is, in Chamberlin's opinion, a species of *fringing glacier*. Such fringes were from a few rods to a half mile in breadth, and where a favorable depression existed, one was observed extending for a mile or more down the valley. Commander Peary has found this a dominant feature on the north Greenland coast. Fringing glaciers of this type have also been described by Salisbury from the vicinity of Melville Bay. Their movement was clearly evinced by their structure and by the débris which they carried.[76a]

Nature of the Surface Snow of the Inland-ice.—The surface snow from the marginal zones of the inland-ice has the granular form characteristic of névés, as has been shown with exceptional clearness in elaborate studies by von Drygalski.[77] Such grains, grown by accretions from a single crystal nucleus and at the ex-

[76] T. C. Chamberlin, "Glacial Studies in Greenland, VI.," *Jour. Geol.*, Vol. 3, 1895, pp. 580–581.

[76a] Salisbury, *Jour. Geol.*, Vol. 3, p. 886.

[77] "Grönland-Expedition," etc., Vol. 1, 1897.

pense of neighboring crystals, must require either fusion from temporary elevation of temperature, or from pressure. The observations of von Drygalski were made on the ice of the marginal tongues and on the blue layers of the inland-ice; but as the samples taken farthest from the margins were found at a height of only 500 meters, the results throw little light upon the conditions of surface snow within the interior, where melting does not take place. In view of recent studies in Antarctica it is unlikely that firn or névé snow will be found within the interior except at considerable depths below the surface.

Nansen has described the fine "frost snow" which falls almost daily from an air layer near the snow surface, from which its moisture has been derived. Melting does not occur there, as already stated, except perhaps for a few days in the height of summer when a thin crust develops upon the surface.[78] Peary has referred to the snow at the highest altitudes which he reached in north Greenland as "unchanging and incoherent." This dry hard snow chased by the wind, has the cutting effect of sand in a blast, and thus is offered still another parallel with deserts and their wind blown sand. Each new storm, we are told by Stein,[79] piles up a snowbank on the lee sides of nunataks, but the next storm, coming from a somewhat different direction and laden with fine hard snow, cuts away the earlier deposit as would a sand blast. Peary discovered one of his earlier snow huts partly cut away by this process.

Snow Drift Forms of Deposition and Erosion—sastrugi.—The minor inequalities of the snow surface as determined by the wind blowing over the inland-ice, have been mentioned more or less persistently by all Arctic travellers, since upon the character of this surface has so largely depended the celerity of movement in sledge journeys. It is unfortunate that no one has discussed the subject from a scientific standpoint, for it has great significance in connec-

[78] "Thus it will be seen that at no great distance from the east coast the surface of dry snow begins, on which the sun has no other effect than to form a thin crust of ice. The whole of the surface of the interior is entirely the same." (Nansen, *l. c.*, Vol. 2, p. 478.)

[79] Robt. Stein, Congrés international pour l'étude des regions polaires. Brussels, 1906, pp. 1–4 (separate).

tion with the study of the strength and direction of the wind over the snow surface. All minor hummocks and ridges of this nature are included under the general term *sastrugi* (see Fig. 31).

The student may learn much concerning their form within the Antarctic regions from examination of the many beautiful photographs recently published by the Royal Society in connection with

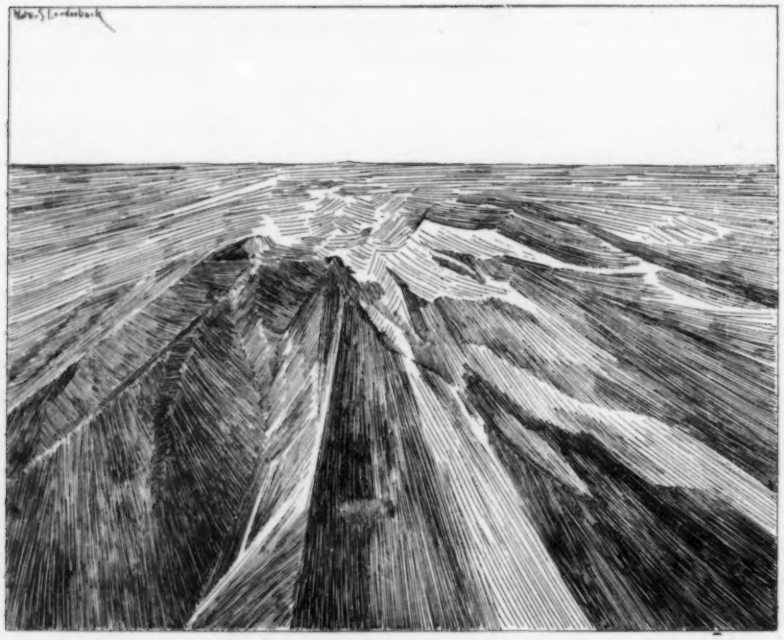


FIG. 31. Sastrugi on the inland-ice of North Greenland (after Peary).

the British Antarctic Expedition.[80] On Plate 92 of this collection, sastrugi are shown which were originally laid down in "elongated domes" and "crescent hollows," but which on account of change in the wind direction the drifting snow granules have cut away both on the soft surface and in the harder deep layers. As a result of this erosion cross flutings have been superimposed upon the original forms.

[80] National Antarctic Expedition, 1901–4. Album of photographs and sketches (with brief descriptions, Ed.), London, 1908.

Our best study of snow drift forms has been made by Dr. Vaughan Cornish, who, after a series of monographs dealing with waves of drifted sand, has spent a winter in Canada in order to study the phenomena connected with the drifting of snow.[81] It is found that snow which falls at temperatures near 32° F. is wet and sticky, and behaves quite differently from that which falls near or below the zero of the same scale; which, on the contrary, is dry and slippery. Subsequent modifications of either of these forms of snow depend chiefly upon pressure, temperature, radiation and wind. It is the cold, dry and granular snow only which makes so-called *normal* waves, and it must be this form which plays the major rôle in producing the surface irregularities of the inland-ice of Greenland.

Ripples and larger waves alike, when formed from granular snow and when shaped by wind accumulation, *have the steep side always to leeward,* in which respect the snow behaves like drifted sand. In order to produce waves or ripples the wind must have a velocity sufficient to be thrown into undulations by the irregularities of the surface over which it blows. The most perfectly moulded forms are naturally produced upon a relatively plane surface, such as is realized on the inland-ice of Greenland—the "imperial highway" of Commander Peary.

Apparently the direction of the greatest extension of the sastrugi will depend upon the strength of the wind and upon the amount of snow which is being transported, much as has been found to be the case with drifted sand.[82] Thus, with small amounts of snow and moderate winds, the characteristic form of sastrugi is a short, scalloped ridge lying across the wind direction and in form not unlike an ox-yoke—something intermediate between a barchan and a transverse ridge. Barchans of snow almost identical in form with sand barchans, are produced apparently under like conditions, the chief differences being that lighter winds suffice

[81] Vaughan Cornish, "On Snow-waves and Snow-drifts in Canada," *Geogr. Jour.,* Vol. 20, 1902, pp. 137–175.

[82] P. N. Tschirwinsky, "Schneedunen und Schneebarchane in ihrer Beziehungen zu äolischen Schneeablagerungen im Allgemeinen," *Zeitsch. f. Gletscherk.,* Vol. 2, 1907, pp. 103–112.

to accomplish the result with the less ponderous snow, and that the resulting forms set quicker in the snow (see Fig. 32, *a*).

Cornish has realized the full importance of snow-blast erosion in modifying the form of snow drifts. His *barchans of erosion,* in plan resemble the barchans of deposition from which they are derived, but unlike the depositional forms their broader surface is concave upward instead of convex, and their steeper face is toward the wind (see Fig. 32, *b*).

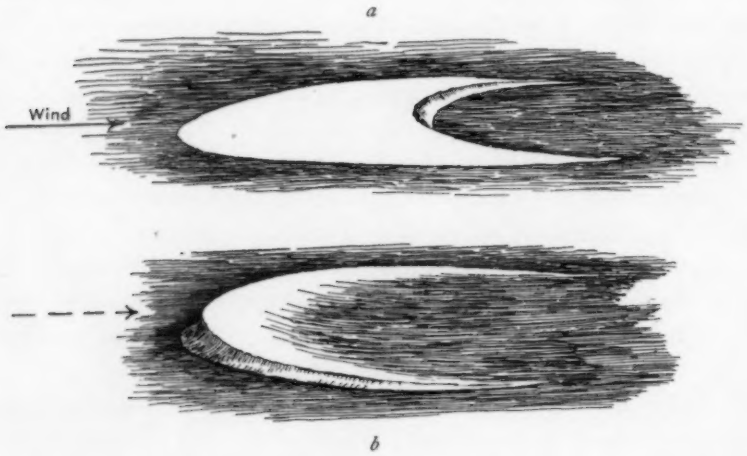


FIG. 32. Barchans in snow. *a*, of deposition; *b*, of erosion (after Cornish).

Some facts of importance which concern the density of the snow are emphasized by Cornish, and apply with especial force to the surface snow of inland-ice. It was found that crusts upon the surface of snow do not necessarily imply melting, but are produced in temperatures below the fusion point. When the air temperatures at Winnipeg ranged from 25° to —28° F. the snow surface over the river set so hard that the mocassined heel did not dent it. Pieces of this snow broken off and held up to the sunlight showed a "mosaic of small translucent icy blocks cemented firmly by opaque ice." The effect upon snow density of the radiation from the surface and of pressure from the wind, were strikingly brought

out by a number of observations. Newly fallen snow in Canada has a density of about 0.1. Over the level surface about Winnipeg in the month of January and at a temperature of 10° F., the snow was found to have a density within the upper two feet of 0.38; while in the woods at the same time and at the same depth, here without a crust, its density was 0.19. Thus it is seen that the snow in the woods is about twice as heavy as newly fallen snow, but only about half as heavy as that which has been chased about by the wind. At Glacier House in the Selkirks, where the snow is shielded from the wind within a narrow valley, experiments showed a density of 0.106 at the surface, whereas at a depth of one foot below the surface the density was 0.195, and at a depth of four feet, 0.354. The middle value being that of the snow in the woods at Winnipeg, it is seen that the weight of an additional three feet of snow is necessary in order to pack snow as tightly as is done by the wind blowing over the prairie. After a time, as a result of this treatment by the wind, an eight-inch snowfall dwindles by packing in the woods to four inches, and over the open plain to a two-inch layer.

In eroding a drift, the wind first attacks the softer surface layer. This removed, the snow of the blast adheres less to the surface of the drift, and in consequence abrades it more vigorously. Thus, notches in the ridges, instead of being mended by the detritus, are increased by it, and transverse ridges are presently cut through, and we pass by stages from an arrangement of ridges transverse to the wind to that of longitudinal structures having the greatest extension parallel to the wind.[83] These longitudinal sastrugi appear to be the dominant ones, and from them the direction of prevailing winds may be determined as has been already proven in the Antarctic. On the Siberian tundras the sastrugi are often the only guides of direction which the natives have.[84]

Source of the Snow in Cirrus Clouds.—What has been learned of the circulation of air above the continental ice of Greenland makes it extremely unlikely that any such excessive alimentation upon the eastern margin through ordinary snow fall, as has been

[83] Cornish, *l. c.*, pp. 159–160.
[84] Tschirwinsky, *l. c.*, p. 107.

advocated by von Drygalski, can occur.[85] Such moisture-laden air as can, under normal conditions, reach the interior plateau must descend from higher levels in the anti-cyclone above the central boss, and be distributed by the outward flowing surface currents. From such altitudes the moisture would probably be congealed in the form of fine ice needles, such as are believed to exist in cirrus clouds. The snow which covers the surface at these levels appears, moreover, to have this character. Of greatest interest in this connection is the observation of Nansen that while the sky was, during the time of his crossing, in the main clear, those clouds which were present were generally either cirrus clouds or some combination of cirrus with cumulus and stratus clouds. No cumulus clouds whatever were observed. In tabular form his results are as follows:

Form of Clouds.	No. of Days.		Per Cent.
Cirrus	23		44
Cirro-stratus	17	51	33
Cirro-cumulus	11		21
Cumulo-stratus	22		42
Stratus	10		19

As already stated, such snow as reaches the central area must, it would seem, be derived from the cirrus clouds which at higher levels move in toward the anti-cyclone and descend as surface currents over the "Great Ice."

Depletion of the Greenland Ice from Surface Melting.

Eastern and Western Slopes Compared.—Though it is probably not true, as has been claimed by von Drygalski, that the eastern border of the continent is the locus of nourishment for the ice, it is almost certain that the losses are much greater along the western margins. For this there are several reasons. In the first place, the eastern base is apparently characterized by lower temperatures. The cold ocean current, which carries ice bergs and flows from the

[85] "The east is to be regarded as the region of origin of snow, the west as the terminal region of the Greenlandic glaciation." (E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.)

Arctic Ocean southward in Baffin's Bay, follows the western shore, while a warmer counter current flows northward along the eastern or Greenland coast at least in its southern stretches. Tarr thinks this current may reach as far as Melville Bay.[86] In addition, the gentler slopes of the western surface of the ice are perhaps more favorable to the warm and dry "thaw wind"—the well-known foehn of Greenland.

Again, ablation or surface melting is to a large extent dependent upon the quantity of rock débris which is blown onto the ice surface from its margins. In southern Greenland, at least, the wider ribbon of exposed shore land upon the western coast conspires with the prevailing western winds to make a more effective marginal attack upon the anti-cyclone of the continent. Nansen reports that he found on the east coast none of the rock dust first described by Nordenskiöld as "cryoconite," though it extended inward from the western coast as much as 30 kilometers.[87]

Still further it is to be remembered that the ice of the west margin is intersected by many deep fjords, which communicating with the open sea, remove an enormous quantity of ice in the form of bergs. Upon the eastern coast the pack-ice prevents the removal of bergs except from the southern latitudes.

Effect of the Warm Season Within the Marginal Zones of the Inland-ice.—In winter the entire surface of the ice and the border of the land as well, are covered with an unbroken layer of fine, dry snow. The suddenness of the change to summer within the land zone outside the ice front, has been emphasized by Trolle. The temperature of the snow upon the land in northeast Greenland rose gradually with the arrival of summer until the melting point was reached, and then in one day all the snow melted. "The rivers were rushing along, flowers were budding forth, and in the air the butterflies were fluttering."[88]

The snow upon the surface of the inland-ice where studied by

[86] R. S. Tarr, "Difference in the Climate of the Greenland and American Sides of Davis' and Baffin's Bay," *Am. Jour. Sci.*, Vol. 3, 1897, pp. 315–320.

[87] Mohn und Nansen, *l. c.*, p. 90.

[88] Trolle, *l. c.*, p. 66.

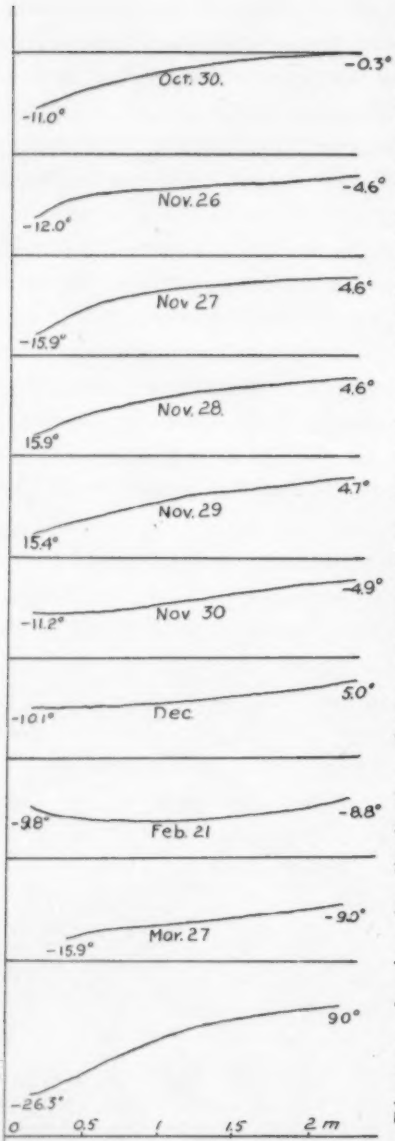


FIG. 33. Diagrams showing the distribution of temperatures within the surface zones of the inland-ice (after von Drygalski).[29]

von Drygalski within the western marginal zone, was found to have temperatures which in the winter season were normally lowest just below the surface, and which approximated to the zero of the centigrade scale at depths of generally a few meters only. In October with a sub-surface temperature of —11°C. the zone of zero temperature was reached at a depth of a little more than two meters. The sub-surface temperature steadily lowered from this time as the colder months came on, and the depth of zero temperature descended to below the limit of the experiments, which was only a little more than two meters. The form of the temperature curves in dependence upon depth showed clearly, however, that at very moderate depths equalization occurred. Late in March the lowest temperatures were reached with —26.3° C. for the immediate sub-surface temperature, and —9° C. for the temperature at depth of two meters. Warm weather at the surface re-

sulted in a warm wave which descended through the snow, following the colder one, and so resulted in a maximum temperature not immediately below the surface but at increasing distances from it depending upon the duration of the warmer air temperatures at the surface. Thus, a ten day foehn in January raised the temperature at a depth of 2.2 meters, by a half a degree. It required over two days for this rise in temperature to proceed to a depth of 1 meter, and ten days for it to reach the depth of 2 meters. Similar effects are produced with the coming of the more prolonged warm weather of the summer season (see Fig. 33).

When the surface zone of the snow has reached the fusing point of snow, melting begins rapidly. Peary has drawn a graphic picture of the effect of the warm season upon the margins of the Greenland ice. Late in the spring the warmth of the sun at midday softens the surface first along the outermost borders of the ice, and this, freezing at night, forms a light crust. Gradually this crust extends up in the direction of the interior, and as the season advances the surface of the marginal rim becomes saturated with water. This zone of slush follows behind the crust towards the interior in a continually widening zone as the summer advances. Within the outermost zone the ice is so decomposed that pools come to occupy depressions upon the surface and streams cut deep gullies into the ice. At the same time the ice shows a more dirty appearance through the concentration of the rock débris due to the melting of its surface layers. By the end of the season, pebbles, boulders and moraines have in places made their appearance on the surface, and the streams have left a surface of almost impassable roughness.[90]

Differential Surface Melting of the Ice.—In his ascent of the western margin of the ice near the latitude of Disco Bay, Peary encountered lakes surrounded by morasses of water saturated with snow. The ice within this zone is crevassed, and down the fissures some of the surface streams disappear, at times in a large water-fall, and again in a "mill" of its own shaping. Baron Nordenskiöld

[89] E. von Drygalski, "Grönland-Expedition," *l. c.*, pp. 460–466.

[90] Peary, *Geogr. Jour.*, *l. c.*, p. 218. See also Nordenskiöld, "Grönland" (German ed.), pp. 125–138.

earlier observed almost identically the same phenomena along the line of his route. The intricate ramifications of the superglacial rivers and the occupation of almost the entire remaining surface of the ice by shallow ice wells and basins along his route are shown in Figs. 34 and 37.[91] These ice wells are in no wise restricted to inland-ice but are found in mountain glaciers as well, and represent but one of a series of allied phenomena dependent upon differential melting due to the presence of fine rock particles upon the ice. They were quite thoroughly described by Agassiz in his "Système

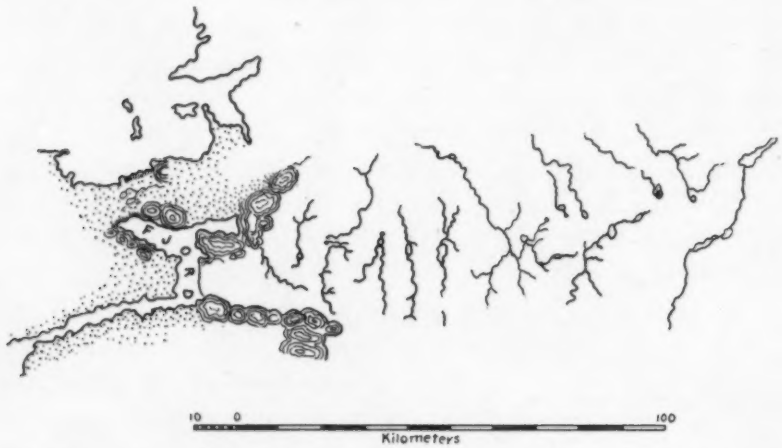


FIG. 34. Map showing the superglacial streams within the marginal zone of the inland-ice of Greenland (after Nordenskiöld).

Glacière." The particles of rock if not contiguous upon the ice surface absorb the sun's rays and cause excessive melting of the ice above and beneath them. They thus sink down into the ice and form dust wells (Fig. 35, *a*). The thin walls which separate those wells which are close together, being now attacked by the warm air on their sides instead of on the top only, they in their turn melt away to form a small basin, which soon either wholly or in part fills with water (Fig. 35, *b*). Where in contact with their neighbors and where of such thickness of accumulation as not to be heated through by the sun's rays, these rock particles behave in quite a

[91] A. E. Nordenskiöld, "Grönland," pp. 197–204, map 3.

different manner and protect the ice beneath them from the sun (note margins of wells and basins in Fig. 35, *a* and *b*). The same effect is brought about if the fragments are too large, for the thick-

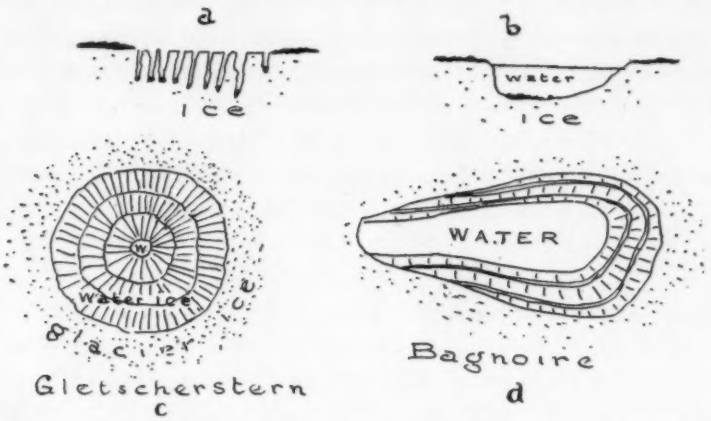


FIG. 35. Diagrams to show the effects of differential melting on the ice surface: *a*, dust wells; *b*, basins; *c*, glacier stars; *d*, bagnoires.

ness of surface layer of rock which can be sensibly warmed by the sun's rays is quite independent of the size of the fragment. Thus

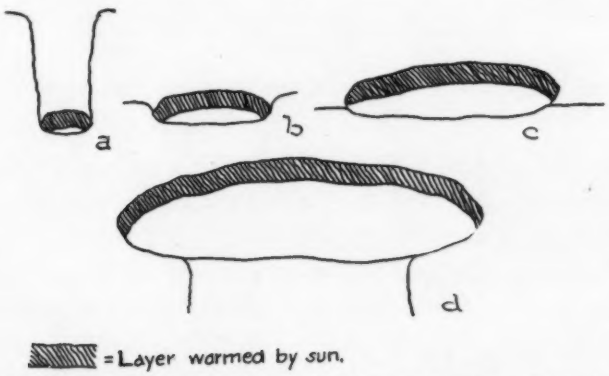


FIG. 36. Fragments of rock of different sizes to show their effect upon melting on the ice surface.

the familiar ice tables developed especially upon mountain glaciers are formed. Fig. 36 brings this out by showing the relation of the

warmed surface layer to the whole fragment—(*a*) in a dust well, (*b*) in a pebble that sinks slightly into the ice until it reaches equilibrium, (*c*) in a slab of such size as to neither facilitate nor retard surface melting, and (*d*) in a large protective slab of rock.

The basins which result from the dust wells induce still other interesting structures. At night the water within these basins freezes in the form of needles which everywhere project inward from the steep walls of the basin. After repeated freezings the basins are often entirely closed by these needles and thus form "glacier stars" (see Fig. 35, *c*). Elongated basins have been given the name bagnoires (see Fig. 35, *d*).

From studies of such phenomena resulting from differential melting as developed upon the Great Aletsch glacier, we have found that the segregation of the rock débris upon the bottom of the basins later protects those areas after melting of the general surface has

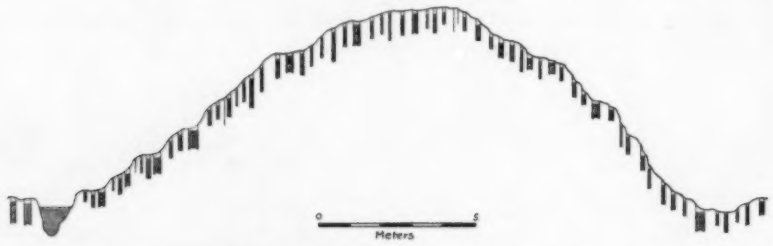


FIG. 37. Section of the so-called "cryoconite holes" upon the surface of an ice hummock (after Nordenskiöld).

drained them of their water. Thus the familiar débris-covered ice cones come into existence and further increase the irregularities of the ice surface. The dust wells and basins which were described by Nordenskiöld covered over large areas the sides of steep hummocks in the ice as well as its more level surfaces (see Fig. 37).

On his return from his attack upon the inland-ice near Disco Bay, Peary travelled for seven hours through half-frozen morasses alternating with hard blue ice honey-combed with water cavities. Then the character of the ice completely changed, the slush and the water cavities disappeared, and the entire surface was granular snow-ice, scored in every direction with furrows, one to four feet

deep, and two to ten feet in width, with a little stream at the bottom of each.[92]

Moats Between Rock and Ice Masses.—Wherever the ice sends a tongue down a valley, the edges of this ice shrink away from the warmer rocks on either side, thus leaving lateral canyons walled with ice on the one hand and with rock upon the other. Down these canyons are the courses of glacial streams.[93] An excellent example of such a lateral stream is furnished by the Benedict glacier (Plate XXIX, *A*).[94]

In most cases where nunataks project through the ice surface, the absorption of the sun's rays by the rock melts back the ice so as to leave a deep trench surrounding the island and much resembling the moat about an ancient castle. Snow drifted by the wind often bridges or partially fills the moat. Upon nunataks forty miles within the border of the ice in northeast Greenland the Danes found water running in the ravines and disappearing under the ice at the margin of the nunatak where it "formed the most fantastic ice-grottoes, where the light was broken into all colors through the crystal icicles."[95]

Such moats have been mentioned by nearly all explorers upon the ice. It has been claimed by von Drygalski that this phenomenon is characteristic of the west coast margin only, more ample nourishment upon the eastern coast making the snow rise about the rock like a water meniscus. In support of this view he cites Garde, who has figured such a case from the extreme south of Greenland.[96] Peary, however, has shown that the moats upon the west coast are often largely filled with snow.[97] Stein mentions this as a common feature after snow storms,[98] and Chamberlin[99] asserts that wherever

[92] *Jour. Am. Geogr. Soc., l. c.*, p. 282.

[93] Peary, *Jour. Am. Geogr. Soc., l. c.*, p. 286.

[94] R. E. Peary, "North Polar Exploration, Field Work of the Peary Arctic Club," 1898–02, Ann. Rept. Board of Regents Smith. Inst. for 1903, 1904, p. 517.

[95] Trolle, *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 65–66.

[96] "Die Eisbewegung," etc., *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.

[97] Peary, *Geogr. Jour., l. c.*, p. 217.

[98] Stein, *l. c.*

[99] Chamberlin, *Jour. Geol.*, Vol. 3, 1895, pp. 567–568.

the motion of the ice is considerable the trench does not appear, but the ice impinges forcibly upon the base of the nunatak.

Englacial and Subglacial Drainage of the Inland-ice.—In addition to the superglacial streams which are so much in evidence, others which are englacial run beneath the surface of the ice, as has often been discerned by putting the ear close to the ice surface. Nordenskiöld reports one instance where water spouted up from the surface mixed with a good deal of air and spray.[100] Salisbury also has mentioned a huge spring upon the surface of the ice in north Greenland that shot up to a distance of not less than ten feet above the bottom of the basin from which it issued. Owing to the fact that near the margin of the ice its surface is much crevassed, comparatively little water can continue to the border in surface streams. Salisbury mentions an instance where an englacial stream with a diameter of about five feet issued from the vertical face which formed the ice front. Most of the water flowing upon the surface descended, however, to the bottom and issued largely below the surface of the fluvio-glacial materials. It is, he says, a rare exception to find a visible stream issuing from beneath the ice at its margin. In most cases, the water undoubtedly comes out in quantities, though beneath the surface of the outwash apron, as could be detected by the ear.[101] Peary has observed that a greater abundance of water issues from beneath the ice-cap in extreme northeastern than in northwestern Greenland.[102]

The Marginal Lakes.—Wherever the ice has withdrawn from the rock surface and where ice drainage permits of it, small lakes marginal to the inland-ice have come into existence. Special interest attaches, however, to those bodies of water which are impounded by the ice itself along its margin, because of the light which is thrown upon the origin of somewhat similar bodies of water about the great continental glaciers of Europe and North America during late Pleistocene times. Attention was called to such ice-dammed lakes situated upon the margin of the Frederikshaab tongue of the inland-ice by the Jensen, Kornerup and Groth expedition of 1878.

[100] A. E. Nordenskiöld, "Grönland," p. 137.
[101] Salisbury, *l. c.*, pp. 806–7.
[102] Peary, *Geogr. Jour., l. c.*, p. 224.

A map of this region was published by Jensen (see Fig. 38).[103] Here the lakes filled with water from the melting of the glacier by which their outlets are blocked, stand at different levels. The Tasersuak on the south standing at a level of 940 feet above the sea, is blocked by ice at both ends and is covered by bergs which are calved from the ice cliffs. This lake drains through a canal upon the ice to a much smaller lake standing at a level of 640 feet, and thence through a small river to the head of the Tiningerfjord. To the

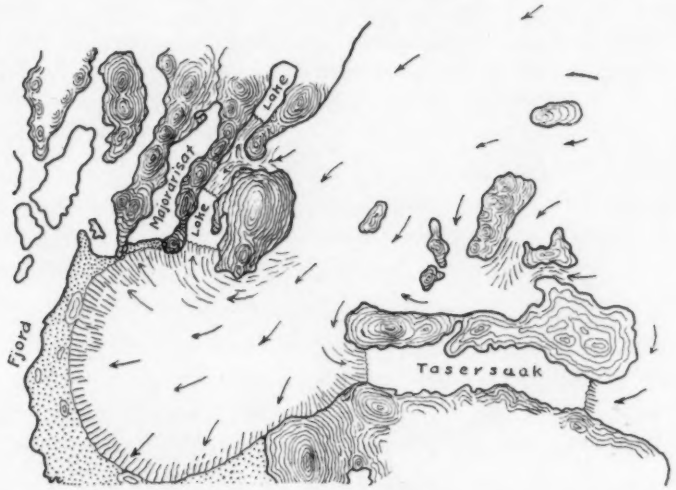


FIG. 38. Map showing the margin of the Frederikshaab ice apron extending from the inland-ice of Greenland and showing the position of ice-dammed marginal lakes (after Jensen).

northward of the apron of ice another long fjord is blocked by a T-shaped extension of ice into its central portion. Thus there result two fresh water lakes standing at different levels, the lower one, like the Tasersuak, with ice cliffs at both ends, and the other blocked at one end only by the ice. A slight retreat of the inland-ice of this district would retire the T-shaped extension of the glacier, and the two smaller lakes would thus become united into one at the level of the lower. A still further withdrawal of the Frederikshaab

[103] "Meddelelser om Grönland," Heft 1. This map has been many times copied, best by Nordenskiöld in his "Grönland" on p. 161.

glacier tongue would open an outlet for this lake to the sea at a still lower level. Souvenirs of these events would be left in a series of parallel shore lines ascending in step-like succession to the head of the fjord (see Fig. 39). Suess has used this illustration to solve the

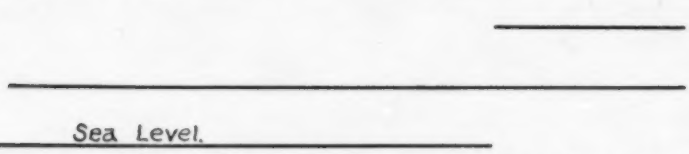


FIG. 39. Diagram showing arrangement of shore lines from marginal lakes to the northward of the Frederikshaab ice tongue, if its front should retire past the outlet of the lower lake.

vexed problem of the *seter*, the abandoned shore lines of Norway which have this peculiarity of arrangement.[104]

The famous "parallel roads" of glens Roy, Glaster and Speen in the Scottish Highlands, which have in similar manner vexed geologists but which were finally given a satisfactory explanation by Jamieson,[105] find here a living model. Still later a nearly identical example from Pleistocene times has been supplied from the Green Mountains to the eastward of Lake Champlain.[106]

About the Cornell tongue of the inland-ice of Greenland are many marginal lakes situated where the border drainage has been blocked by the glacier itself. These lakes have been described by Tarr, who says:[107]

> In its passage down the valley, between the ice and the land, the marginal stream finally enters the sea. During its passage it now and then encounters tongues of ice, and for a distance flows along them, and finally beneath them, where the glacier edge rests against a moraine, or the rock of the land. Again it falls over a rock ledge as a cascade, or even a grand waterfall; and every here and there it is dammed to form a marginal lake.

[104] Besides the Jakobshavn ice tongue, there is another lake confined in like manner to the Tasersuak. (Ed. Suess, "The Face of the Earth," Vol. 2, pp. 346–363.)

[105] Thomas T. Jamieson, On the parallel roads of Glen Roy and their place in the history of the glacial period. *Quart. Jour. Geol. Soc.*, Vol. 19, 1863. pp. 235–259.

[106] Because here the ice similarly blocked the natural outlet.

[107] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geol.*, Vol. 20, 1897, pp. 150–151.

Dozens of these, great and small, were seen along the margin; and they varied in size from tiny pools to ponds half a mile in length, and 200 to 300 yards in width.

Since the water of the marginal streams is everywhere milky with sediment, these lakes are receiving quantities of muddy deposits, and in them tiny deltas are being built. Where the lake waters bathed the ice front little icebergs are coming off, in exactly the same way as in the fjord at the glacier front, and these are bearing out into the lake large rock fragments which are being strewn over the bottom or on the shores. Also at the base of the cliffs, as well as on some of the deltas formed by rapidly flowing streams, pebbles and boulders are being mixed with the clay.

Nearly every lake shows signs of alteration in level resulting from the change in outflow either to some point beneath the ice, when the lake may be entirely drained, or to some lower outlet for the lake opened by a change in the ice front, or by the down cutting of the stream bed where it is eating its way through a morainic dam. The different elevations are plainly evident from the absence of lichens on the rocks, the clay clinging to the rocky shores, and the beach terraces along the old shore lines. In one case, at the western end of mount Schurman, a lake of this type, with a depth of at least 100 feet has recently been drained. Where these extinct lake beds exist one sees revealed an expanse of muddy bottom with scattered blocks of rock.

In Plate XXX, *A* and *B* are represented after Tarr, in the one case, one of the marginal lakes, and in the other, the formation of a delta under the conditions described. From the Karajak district on the northern side of the Upper Nugsuak Peninsula[108] von Drygalski has described in addition to the usual rock basin lakes left by the withdrawal of the ice front, a true ice-dammed lake which appears upon his map as the *Randsee*.[109]

No one of the marginal lakes thus far described furnishes a parallel to the interesting Pleistocene glacial lakes of the Laurentian basin of North America, since these developed for the most part upon a surface of relatively mild relief, and the shores not formed by the glacier itself were generally moraines registering an earlier position during the retirement of the ice front. Perhaps an existing example comes nearest to being realized in connection with those glaciers which descend the eastern slopes of the Andes and enter the great lakes impounded behind moraines of an earlier

[108] "The Cornell tongue is situated upon the southern side of the same Peninsula."

[109] E. von Drygalski, "Grönland-Expedition," Vol. 1, pp. 61–63.

extension of the same ice tongues.[110] In these cases the ice fronts of the glaciers are cut back into cliffs from which are derived the bergs that float upon the surface. The ice cliff and some of the bergs of Lake Argentino are shown in Plate XXX, *B*. According to Moreno, Lake Tyndall is bounded on the west by true inland-ice, the remnant of the larger sheet of Pleistocene times.

Ice Dams in Extraglacial Drainage.—In north Greenland outside the ice front, the brooks sometimes offer a striking example of ice obstructions forming by irrigation. This is often the case where their beds are wide and are covered with boulders. The water generally continues to run beneath the stones for a great part of the winter. Later, however, its outlets may freeze up, whereupon the water rises, inundating the stones and covering them with an ice crust. Through successive obstruction, overflowing and freezing of these streams, the ice dam which results may attain to such a thickness that it is still to be found at these places late in the summer when the ice and snow have elsewhere disappeared from the low land.[111] The significance of such dams as obstructions during a readvance of the ice front may well be considerable.

Submarine Wells in Fjord Heads.—Rink states that the sea flowing into the fjord in front of the glacier tongue which ends below the water level, is kept in almost continual motion by eddies not unlike those which are seen where springs issue from the bottom of a shallow lake. Such areas upon the surface of the fjord may generally be recognized by the flocks of sea birds which circle above them and now and then dive for food.[112] The existence of such fresh water streams as this implies may also be inferred from the strong seaward current that prevails in the fjords and which is so effective in clearing them of bergs. Such a whirlpool of fresh water or "submarine well" was observed by Rink in the Kvanersok-

[110] Francisco P. Moreno, "Explorations in Patagonia," *Geogr. Jour.*, Vol. 14, 1899, pp. 253–256. Also Hans Steffen, "The Patagonian Cordillera and its Main Rivers between 41° and 48° South latitude," *ibid.*, Vol. 16, 1900, pp. 203–206. Also Sir Martin Conway, "Aconcagua and Tierra del Fuego," London, 1902, pp. 134–135.

[111] Henry Rink, "Danish Greenland, Its People and its Products," London, 1877, p. 366.

[112] Rink, *l. c.*, pp. 50, 360–363.

fjord (lat. 62° N.) which was over 100 yards in diameter. The kittiwakes swarmed over the spot, and the water was muddy, although no brooks were observed along neighboring shores. This well Rink believed, from reports furnished by the natives, to be much smaller than the similar ones in some other fjords.

According to Rink[113] the lateral lake which borders the inland-ice of Greenland in one of the branches of the Godthaabfjord-Kangersunek, suffers changes of level just when the submarine wells before the ice cliff in the fjord showed marked changes in volume. Thus, whenever the water of the lake suddenly subsides, the submarine wells from the bottom of the fjord burst out with violence. On the other hand, when the water in the lake is rising, the wells are relatively quiet. These sudden discharges of the water from lateral lakes, save only that their outlet is submarine, seem to be in every way analogous to the spasmodic discharges of the Märjelen See upon the margin of the Great Aletsch Glacier in Switzerland. When, as occasionally happens, this lake empties through the opening of a passage beneath the glacier, the villages which are situated miles below in the valley are suddenly inundated with water.

Discharge of Bergs from the Ice Front.

The Ice Cliff at Fjord Heads.—Wherever the inland-ice reaches the sea in the fjord heads, and where it comes directly to the sea in broad fronts, as it does near Melville Bay, at Jokull Bay and on the north side of northeast Foreland, it is here attacked directly by the waves and is further undermined through melting in the water. The crevassing of its surface over the generally steep descents to the fjords, in a large measure facilitates the attack of the water upon the ice by offering planes of weakness similar to the joint planes in rock cliffs attacked by the sea on headlands. The fjords, though often quite narrow, are generally of great depth, so that although the ice cliff often rises to a height of several hundred feet, and in such cases must be assumed to descend to a depth below the surface of from five to seven times this distance, its base probably everywhere rests upon the bottom of the fjord. To this a possible exception

[113] Rink, *l. c.*

has been noted for the great Karajak glacier, of which a relatively flat front section may be assumed to be the surface of a floating portion[114] (see Fig. 40). To this interesting example of a floating glacier tongue in connection with the inland-ice of the northern hemisphere, we may recall the probably floating front of the Turner

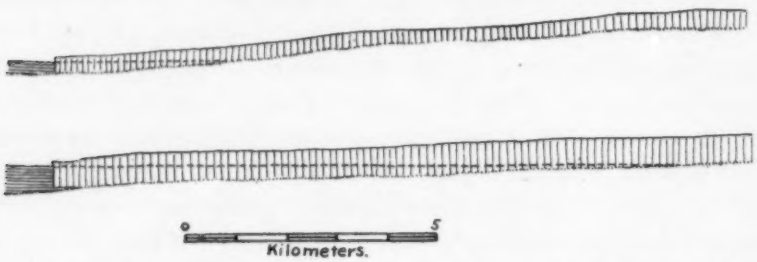


FIG. 40. Sections from the inland-ice through the Great and Little Karajak tongues to the Karajak fjord (after von Drygalski).

glacier, a dendritic glacier of the tide-water type in Alaska. For its type this example is apparently unique.[115]

Manner of Birth of Bergs from Studies in Alaska.—The birth of bergs from the parent glacier has been often described by travellers and the superlatives of the language have been drawn upon to express the grandeur and beauty of the observed phenomena. Simple as the process may appear to the casual tourist who makes the usual summer excursion to Alaska, it is not free from serious difficulties, and has given rise to conflicting views among specialists. The water in front of the ice cliff is generally so muddy, and the danger of approaching the ice front so great, that exact data are necessarily difficult to obtain. The smaller bergs composed of white ice, which are seen to fall into the water from the cliffs at almost all hours, offer no difficulties of explanation, but they are likewise without great significance as concerns the manner of formation of those great floating masses of ice which are carried far

[114] E. von Drygalski, "Grönland-Expedition," Vol. 1, pl. 43. See also R. D. Salisbury, The Greenland Expedition of 1895. *Jour. Geol.*, vol. 3, 1895, p. 885.

[115] R. S. Tarr, and B. S. Butler, "The Yakutat Bay Region, Alaska, Physiography and Glacial Geology," Prof. Pap. No. 64, U. S. Geol. Sur., 1909, pp. 39–40, pl. 10–a.

to sea and scattered over wide areas of the ocean before their final dissolution in the warmer southern waters.

The larger bergs instead of falling from the cliffs, suddenly rise out of the water as ice islands, often several hundred feet in front of the ice cliff. A wholly satisfactory solution of the problem of their birth involves a nice quantitative adjustment of several factors, all of which are undoubtedly more or less concerned. On the one hand, there is wave action which is effective especially near the water level and has a direct range of action extending from a distance below the surface equal to the length of a storm wave in the fjord, and to a height above the quiet level equal to the height of the wave's dash. If there were no melting in the water, and if the lower layers of the glacier moved forward as rapidly as the upper, the tendency would undoubtedly be to develop an erosion profile in every way like that of a rock-cut terrace upon the sea shore. With emphasis upon this element in the problem Russell has assumed that the ice cliff at the fjord is prolonged outward beneath the water as an ice foot which thins gradually toward the toe. Upon this hypothesis the bergs which rise from the water are born from the foot where the increasing buoyancy of the outer portion overcomes the cohesive strength of the material at the surface where rupture occurs. This view accounts particularly well for those bergs which rise from the water far in advance of the cliff (see Fig. 41).[116]

Laying stress rather upon melting in the water and upon the rapid forward movement of the upper layers of ice near the glacier margin, Reid has arrived at a wholly different conclusion concerning the origin of larger bergs:[117]

> The more rapid motion of the upper part would result in its projection beyond the lower part, and this would become greater and greater until its weight was sufficient in itself to break it off. The extent of the projection before a break would occur, depends evidently upon the strength of the ice. . . . That the ice for several hundred feet below the surface does not in general project farther than that above is evident from the fact that I have frequently seen large masses, extending to the very top of the ice front,

[116] I. C. Russell, "An Expedition to Mt. St. Elias, Alaska," *Nat. Geogr. Mag.*, Vol. 3, 1891, pp. 101–102, fig. 1.

[117] H. F. Reid, "Studies of Muir Glacier, Alaska," *ibid.*, Vol. 4, 1892, pp. 47–48.

shear off and sink vertically into the water, disappear for some seconds, and then rise again almost to their original height *before* turning over. If there were any projection within 300 feet of the surface this mass would have struck it and been overturned so that it could not have arisen vertically out of the water.

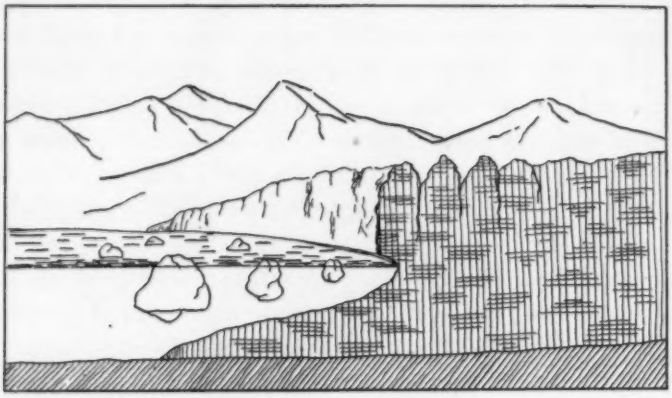


FIG. 41. Origin of bergs as a result especially of wave erosion (after Russell).

Reid thinks there are three ways in which bergs come into existence at the end of a glacier:

(*a*) A piece may break off and fall over—this is the usual way with small pinnacles; (*b*) a piece may shear off and sink into the water—this is the usual way with the larger masses; or, again, (*c*) ice may become detached under water and rise to the surface.

The supposed successive forms of the ice front, according to Reid, are shown in Fig. 42.

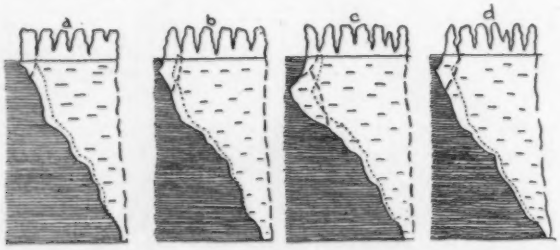


FIG. 42. Supposed successive forms of a tide-water glacier front (after Reid).

It is easy to see that Russell's and Reid's views might each apply in special cases dependent: (*a*) upon the narrowness or the sinuosities of the fjord, which would determine the reach of the waves; (*b*) upon the steepness of the slope back of the ice cliff, which would regulate the different velocities of surface and bottom layers of ice, and determine the measure of crevassing; (*c*) upon the irregularities in the floor of the ice tongue, which would largely fix the amount of shearing and overthrusting; (*d*) upon the presence or absence of warm ocean currents, which would regulate the rate of melting of the ice by the fjord water; and (*e*) upon the freezing of the water surface.[118] which must put a bar upon the action of the waves during the colder period.

Studies of Bergs Born of the Inland-ice of Greenland.—Though ice bergs are discharged from the inland-ice throughout practically the entire extent of the coast line of Greenland wherever inland-ice reaches the sea, yet the great bergs which push out into the broad Atlantic arise either on the west coast between Disco Bay and Smith Sound, or on the east coast south of the parallel of 68°. To the north of this latitude the bergs are firmly held in the heavy pack-ice, while the bergs of southwest Greenland form for the most part in such narrow fjords that they are too small to travel far before their final dissolution.

The size of the Greenland ice bergs has probably been much overestimated. Of 87 measurements made by von Drygalski on the large bergs calved in the Great Karajak fjord, the highest reached 137 meters above the water, or about 445 feet. This mass of ice was, however, against the glacier front, and probably rested on the bottom. None of the others measured were much above 100 meters high or about 325 feet.[119] The berg shown in Fig. 43, photographed by an earlier explorer in Melville Bay, measured 250 feet in height.

During fourteen months spent in the immediate vicinity of the steep front of the Great Karajak ice tongue, von Drygalski carried out extensive studies upon the calving of bergs, and has distinguished three classes. Those of the third class form almost con-

[118] R. S. Tarr, "The Arctic Ice as a Geological Agent," *Am. Jour. Sci.*, Vol. 3, 1897, p. 224.

[119] E. von Drygalski, "Grönland-Expedition," etc., *l. c.*, pp. 367–404.

stantly and consist of larger or smaller fragments which separate along the crevasses and fall into the sea. Only twice were calvings of the second class observed, namely, in late October and in early November. Of one of these von Drygalski says:

> I heard a thundering noise, but at first neither I nor the Greenlanders who were with me saw anything. Suddenly a great distance away from the margin of the glacier, an ice berg emerged from the sea, rose out of the water, though not to the height of the cliff, and then moved away accompanied by a continuous loud tumult and by a rise in the level of the water, through the agency of which it moved away from the cliff quite rapidly. It did not come from the cliff, but certainly emerged from below. The Greenlanders, whom I afterwards questioned about it, gave me the same impression. . . . The margin of the glacier was unchanged.

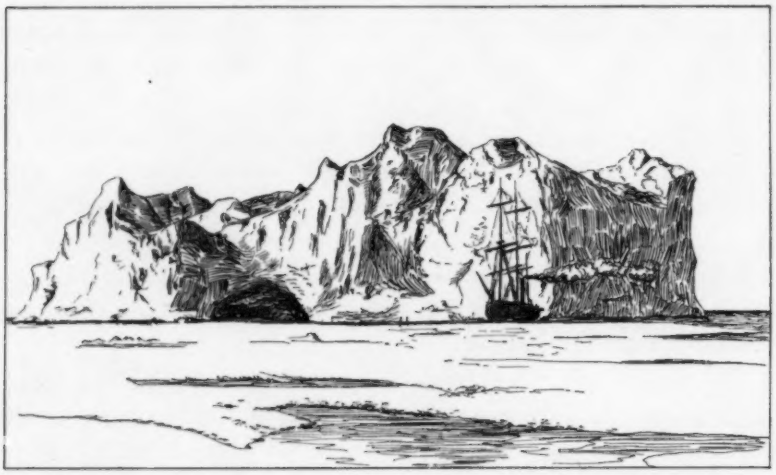
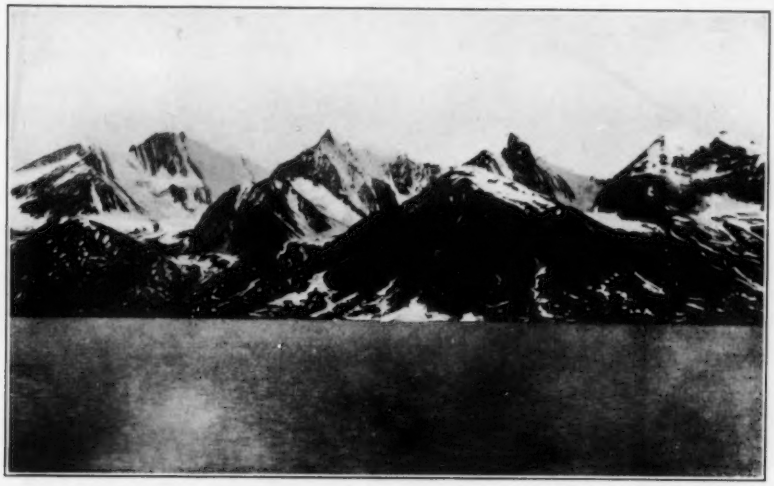


FIG. 43. A large berg floating in Melville Bay and surrounded by sea ice.

Here it was noticed that the berg was long though not as high as the ice cliff which terminated the glacier. It is the opinion of von Drygalski that bergs of this class come from the lowest layers of the glacier. Because of the pack-ice which in winter forms in front of the glacier, the ice cliff is at that time not cut away so fast, and it was, in fact, observed in the winter farther out than during the summer. This explanation in the main is in agreement with that of Russell.

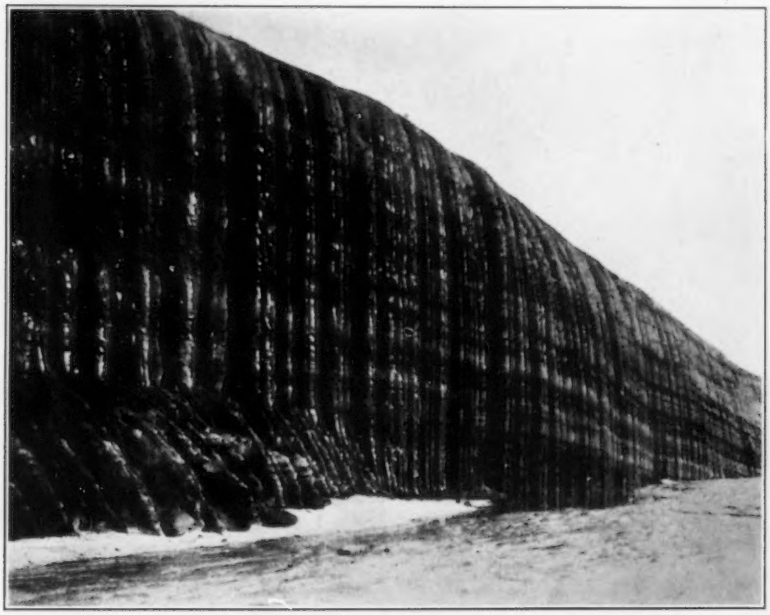
Bergs of von Drygalski's first class, which are the most massive of all, separate from the entire thickness of the ice front. Two



A. Fretted upland carved by mountain glaciers about King Oscar's Fjord, eastern Greenland. The highest points are from 1,360 to 1,570 meters above the sea (after Nathorst).

B. Front of the Bryant glacier tongue showing the vertical wall and stratification of ice. It also shows the absence of rock débris from the upper layers (after Chamberlin).

A. Portion of the southeast face of the Tuktoo glacier tongue showing the projection of the upper layers apparently as a result of overthurst (after Chamberlin).



B. Ice-face at eastern margin of the inland-ice of Greenland in latitude 77° 30′ N. (after Trolle).

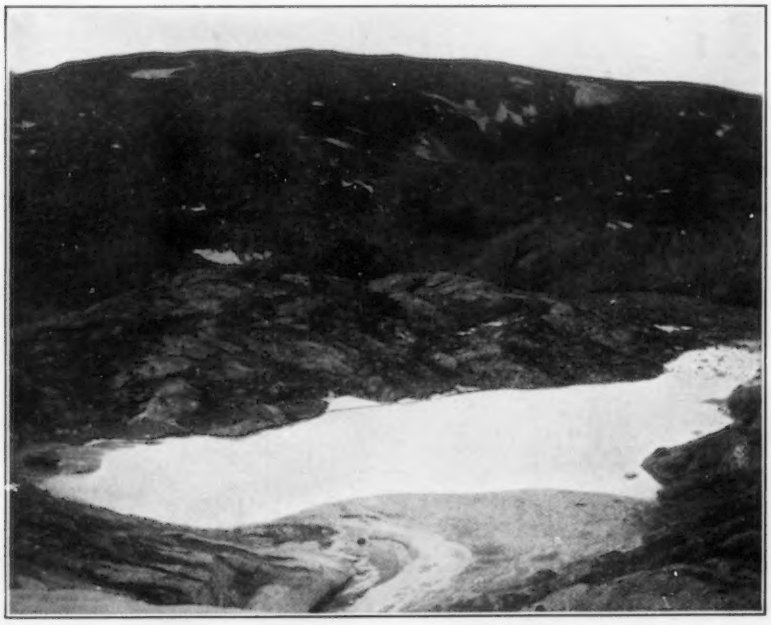
A. Normal slope of the inland-ice at the land margin near the Cornell tongue (after Tarr).

B. Hummocky moraine on the margin of the Cornell glacier tongue (after Tarr).

A. Lateral glacial stream flowing between ice and rock, Benedict glacier tongue (after Peary).

B. The ice-dammed lake Argentino in Patagonia (after Sir Martin Conway).

A. Ice-dammed lakes on the margin of the Cornell tongue of the inland-ice (after Tarr).



B. Delta in one of the marginal lakes to the Cornell glacier tongue (after Tarr).

such bergs were observed in process of calving by von Drygalski and other members of his party. The same loud sound which had been heard at the birth of bergs of the second class accompanied the birth of those in the first class, *but the movement of separation from the glacier was visible at the same instant.* A portion of the cliff front was seen to separate from the cliff, being thereby thrown somewhat out of equilibrium and started in a pendular vibration which produced great waves in the fjord and increased slightly its distance from the newly formed ice cliff. It was here observed that the main pinnacle of the berg slightly exceeded in height the highest pinnacles of the new glacier rim. This, it will be remembered, is in contrast with the bergs of the second class which did not reach to the height of the cliff. Bergs of the first class usually regain their equilibrium after rhythmic oscillations and float away in an upright position. The bergs of the second class often turn over displaying the beautiful blue color of the lower layers. Salisbury's two types of Greenland icebergs seem to correspond with von Drygalski's bergs of the first and second classes.[119a]

The water waves which are sent out to the shores at the birth of a great ice berg extend 50 kilometers or more within the fjord, driving the smaller floating bergs together and thus assisting in their fragmentation and consequent dissolution. The calving of bergs of the first class von Drygalski believes occurs where the depth of the fjord has so far increased that the ice begins to leave the bottom and assume a swimming attitude. The buoyancy of the water is, he believes, thus the true cause of the separation of the bergs.

> Depths which are four to five times as great as the thickness of the inland-ice above the sea level, are not measured in Greenland in front of attached ice masses, because the latter become in that case broken up into ice bergs.[120]

This view gains strength from Salisbury's studies of the glaciers ending in Melville Bay and apparently floated for a very short distance back from their fronts and generally in the middle only.[120a]

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[119a] *Jour. Geol.*, Vol. 3, pp. 892–897.

[120] E. von Drygalski, *l. c.*, p. 404.

[120a] Salisbury, *Jour. Geol.*, Vol. 3, 1895, pp. 885–886.

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SOLAR ACTIVITY AND TERRESTRIAL MAGNETIC DISTURBANCES.

By L. A. BAUER,

Director of Department of Research in Terrestrial Magnetism, Carnegie Institution of Washington.

(*Read April 23, 1910.*)

It has already been my privilege to lay before this society, on various occasions, some of the results obtained since 1905 of the magnetic survey work, chiefly of the oceans, conducted under the auspices of the Carnegie Institution of Washington. At the present rate of progress it seems reasonable to suppose that by the year 1915 it will be possible to construct a new set of magnetic charts as based upon homogeneous data largely obtained by one organization. Along with the magnetic survey of the oceans, begun on the "Galilee" in the Pacific Ocean in 1905 and continued until May, 1908, and now being conducted on the "Carnegie" in the Atlantic Ocean and later to be extended to the Indian Ocean, that of land areas is likewise in good progress, parties of the Carnegie Institution of Washington having already made notable expeditions in magnetically unexplored regions in all parts of the globe.

Provision has thus been made for a rapid and continuous accumulation of the data required for mapping the so-called "permanent" magnetic forces of the earth. As a matter of fact, however, the earth's magnetism is subject to continuous change, and owing to the so-called secular changes but a few years—five to ten—suffice to completely alter a chart showing the direction of the compass at various points over the globe. Hence, the work as being executed likewise embraces the determination of the secular changes in the earth's magnetism at a sufficient number of stations to permit applying the necessary corrections for keeping magnetic charts up to date.

However, there is another side to magnetic work, certainly not

less interesting, and possibly equally important to that mentioned—the investigation of the causes of those mysterious influences which daily, hourly, year in and year out, impress themselves upon the earth's magnetism. It is confidently believed by many that we must look primarily to the fluctuations of the delicately poised and sensitive magnetic needle for the key which will unlock the door to knowledge of the mysterious forces, coming from the regions beyond and conditioning the phenomena on which our welfare and development may, in no small measure, depend.

But aside from any such possible practical results, the belief is not without foundation that just as the great doctrine of evolution resulted from the persistent and searching inquiry into the causes producing the variations and mutations in biological phenomena, *our knowledge of the earth's magnetism is primarily to be advanced through the study of what causes the earth's magnetism to vary.* It also appears that when we shall have made an exhaustive study of the periodic magnetic variations, such as the solar-diurnal, the lunar-diurnal, the annual, etc., we shall find that none of these is strictly cyclic, but that each runs its course, through periods incommensurable with one another, the resulting residual effects at any moment of time being of sufficient magnitude to be reckoned with. Thus it may be possible to account for the secular variation of the earth's magnetism without resorting to any other cause than those daily in operation.

I shall now give a sketch of the chief results obtained along a line of inquiry being conducted coöperatively between two departments of the Carnegie Institution of Washington—the Solar Observatory at Mt. Wilson, California, under the direction of Professor George E. Hale and the Department of Research in Terrestrial Magnetism—viz., as to *the connection between solar activity and the earth's so-called magnetic storms.*

At an instant, without any previous warning, magnetic needles are caused to swing out of their usual position or direction, earth electric currents are generated of sufficient strength to interfere with telegraph and cable lines, brilliant and wide-spread auroras are evoked, and even electric car line traffic is momentarily suspended—by what? That is the problem. Possibly at the same time there

may be seen remarkable formations of sun-spots and the conclusion is drawn that there is some connection between the solar and terrestrial phenomena, especially so as similar coincidences have very often occurred in the past.

However, the connection is far from being such an immediately evident one. Many cases of magnetic storms might be cited when no sun-spots existed, at least on the face of the sun then visible. Then again, the area of a sun-spot is no true index either of the character or of the magnitude of a magnetic storm which may occur at about the same time. Thus one of the severest magnetic storms within the past fifty years—that of October 31 to November 1, 1903—was associated with a group of sun-spots considerably smaller than that in the earlier part of the month which was accompanied by a minor magnetic disturbance. Attempts at a direct connection between individual sun-spots and individual magnetic storms have not been wholly successful. While there have been a few cases—very few in fact—in which an apparently immediate connection was discovered between some striking solar phenomenon and a terrestrial magnetic fluctuation, there are vastly more instances for which no such individual relation existed. If, however, the subject is approached statistically, and the average state of the solar surface, as gauged by sun-spots or other eruptive phenomena, is compared with the average state of the earth's magnetism for a sufficient interval of time—a year or say several months—and these average values plotted, then a most striking resemblance is manifested between the two sets of phenomena. The parallelism, as intimated, is not so pronounced, however, for shorter intervals, for example that of a month.

The magnetic data generally used in such comparisons are the ranges or amplitudes of the daily fluctuations of the magnetic needle or say the frequencies of magnetic storms. During years of high sun-spot frequency, *i. e.*, increased solar activity, the diurnal swing of the needle is very appreciably greater than in years of low sun-spot frequency. And likewise without question the greatest number of, as well as generally the severest, magnetic storms occur in years of increased solar activity. While investigations exhibit a linear relationship between the average sun-spot frequencies and the

average diurnal range for a fairly long interval of time, so that one set of phenomena could be almost directly deduced from the other, a similar relation has not been found to hold between the *magnitude* of a magnetic disturbance and any measure of solar activity thus far proposed.

Fresh interest was shown in magnetic storms a year ago by Hale's discovery of magnetic fields in sun-spots and some persons immediately jumped to the conclusion that the origin of our magnetic storms had been discovered. However, the rapid decrease in the strength of the sun-spot fields with elevation, observed by Hale, shows that they, at the distance of the earth from the sun, could not by direct action produce an effect to be detected by the most sensitive modern magnetic apparatus, whereas the effects actually observed during a magnetic storm exceed by 100 and even 1,000 times the limit of measurement. It ought to be stated that Hale himself never, as far as I know, expressed any opinion as to the possibility of a direct magnetic action of sun-spots.

In order to pave the way towards a solution of some of the difficulties mentioned, the following investigation was originally begun, partly as the result of a desire on the part of Professor Hale to ascertain as quickly as possible what solar phenomena should be given chief attention in the proposed study. He wished to know, for example, how closely the curves resulting from his new method of measuring the solar activity—by the total area of the bright calcium flocculi seen on the sun's disc—corresponded with the well-known fluctuations in the earth's magnetic activity. He divided the sun's disc into zones 10° wide and determined the area of all the flocculi present in each zone. The sum of all the zones is the total area for the period in question and the solar activity was taken to be directly proportional to this area. Since the rotation period of the sun varies with solar latitude, means are taken for each zone corresponding to the rotation period for that zone in order to eliminate the effect of the solar rotation.

In my paper presented to the society a year ago I was enabled to communicate some preliminary results obtained from our comparative study of the variations in the sun's activity, as shown by the calcium flocculi measurements at the Mount Wilson Solar Observa-

tory for the period May, 1906, to January, 1909, and the variations in terrestrial magnetic activity during the same period, as based upon the observations at the five magnetic observatories of the U. S. Coast and Geodetic Survey. Probably the most important result then derived was that, in general, the earth's magnetization suffers a diminution during a period of intense solar activity. This pointed to the fact that the general, or average effect, of a magnetic storm was to superimpose on the earth's magnetization a system of magnetic forces equivalent to a demagnetizing system whose magnetic axis was reversed from that of the earth's magnetic field, so that the magnetic north pole of the disturbance system would lie in the southern hemisphere. While this relation between changes in solar activity and those in the earth's magnetism held, in general, for the period examined (May, 1906–January, 1909) there were some manifest contradictions also, so that for these an increase in solar activity corresponded to an increase in the earth's magnetization. These same contradictions were found to hold generally if we replaced Hale's measure of solar activity by the Wolfer curve of sun-spot frequency. There was thus again revealed the difficulty of establishing a relation which would link solar with magnetic phenomena in such a definite way that one set might be predicted from the other.

Additional discoveries regarding terrestrial magnetic disturbances may now be reported upon. A recent examination of the times of beginning of magnetic disturbances, as recorded at observatories over the entire globe, showed that, without doubt, magnetic storms do not begin at absolutely the same instant of time, as heretofore believed. Instead, they are found to progress over the earth in some definite manner and at a measurable speed. For the abrupt disturbances, which are usually comparatively minute in their effect on the compass needle, a complete passage around the earth would require from 3½ to 4 minutes. For the bigger effects, or for the larger magnetic storms, the differences of time between various stations are such that if these larger effects also traveled around the earth completely, it might take them a half hour or more. The following main conclusions were drawn:[2]

[2] *Journal Terrestrial Magnetism and Atmospheric Electricity,* Washington, D. C., Vol. 15, No. 1, March, 1910 (18 and 20).

It is thus seen that the disturbances of May 8, 1902, and of January 26, 1903, both traveled around the earth eastwardly, at an average velocity of about 6,700 miles per minute, taking from 3½ to 4 minutes to make the complete circuit. The disturbance of May 8, 1902, as determined from the times of beginning at the various stations, began in about the meridian of 75° west, whereas the initial meridian for the disturbance of January 26, 1903, computed in a similar manner, was found to be, roughly, 160° west. . . .

Magnetic storms do not begin at precisely the same instant all over the earth. The abruptly beginning ones, in which the effects are in general small, are propagated over the earth more often eastwardly though also at times westwardly, at a speed of about 7,000 miles per mnute, so that a complete circuit of the earth would be made in 3½ to 4 minutes. For the bigger and more complex magnetic disturbances the velocity of propagation may be cut down considerably. The time of beginning of the disturbance may be appreciably different, for the various magnetic elements, according to the character of the operating systems.

The moment it is granted that magnetic storms do not occur over the earth simultaneously, then a new point of view is presented for the investigation of the relation between magnetic storms and solar activity, and a definite criterion is set for testing any theory advanced. A second decisive test is furnished by another important fact disclosed by our study of the direction of motion of the two magnetic disturbances of May 8, 1902, and January 26, 1903. The electric currents which we should have to suppose circulating in the regions above us to produce the disturbance effects as actually recorded for the cases cited, would have to go around the earth eastwardly, if they are to be ascribed to a motion of negatively electrified particles. This is in fact the very direction in which the times of beginning of the disturbances were found to progress.

Were we to suppose now that magnetic disturbances are due to the entrance in the earth's magnetic field of small negatively electrified particles brought to us from the sun by the pressure of light, or were we to adopt the hypothesis of cathode rays coming from the sun, then, in either case, it would be found that the effect of the earth's magnetic field is to deflect these particles in such a way that, in the equatorial regions, for example, they would be made to circulate around the earth from east to west. But this direction is contrary to that in which we found the negative electric currents would have to go for the disturbances of May 8, 1902, and January 26, 1903, to harmonize with the times of beginning noted at stations

around the globe, and as shown to be necessary to account for the actual disturbance effects. Hence the direction test already excludes the possibility of ascribing certain of our magnetic storms, at least, to the effect of negatively electrified particles and cathode rays received from the sun. In a similar manner, it can be shown that positively electrified particles would likewise not accomplish the desired result.

But the time required for the quickest disturbances to get around the earth—about 3½ to 4 minutes—furnishes another crucial test. Knowing the electric charge carried by the particles, their velocity, and the deflecting effect of the earth's magnetism, it is possible to compute the radius of the circle around which they would have to move were they to come to the earth approximately, for example, in the plane of the equator and accomplish the circuit in 3¾ minutes. This radius turns out to be 580 times that of the earth's radius. Hence, these particles could never approach the earth closer than 2,300,000 miles! And if we compute the strength of the current necessary to produce at that distance even one of these comparatively minute magnetic disturbances, we find it would have to be on the order of 60,000,000 amperes, or sixty times that deemed sufficient to account for the big disturbances. We are accordingly forced to look elsewhere for the chief source of our magnetic storms. [The value of the radius, 2,300,000 miles above given applies to an electronic mass. Where we to increase the latter 1,000,000 times the radius would still be 23,000 miles. If we take the mass of the carrier of the electric charge the size of that of a particle brought to us by the pressure of light, the radius turns out less than that of the earth, hence an impossible result.]

In addition to negatively electrified particles coming from the sun, we also receive radiations such as the gamma rays of radium or the Röntgen rays, which are not deflected by the earth's magnetic field as they do not carry electric charges. Their chief effect would be to ionize the gases of which the atmosphere is composed, *i. e.*, make these gases better conductors of electricity. Ultra-violet light has the same effect. Now we know that a small part of the magnetic forces acting on a compass needle is due, not to magnetizations or electric currents below the earth's surface, but to electric

currents in the atmosphere. If then the regions of these upper electric currents are at any time made by some cause more conducting, electricity is immediately set in motion, which in turn induces a subsidiary magnetization in the earth. The effect then which we actually observe on the compass needle is the joint result of the newly generated electric currents in the atmosphere and the induced magnetization of the earth.

The direction followed by the new current depends upon its origin, upon the direction of the electromotive force of the primary electric field already existing at that point, and upon the deflecting effect of the earth's magnetic field and of the earth's rotation on the flowing current. *In other words, while we must doubtless look chiefly to extra-terrestrial agencies for the ionizing of the air and thus splitting it up into carriers of positive and of negative charges, we are compelled to look to the atmospheric electric field and to the earth's rotation for furnishing the energy necessary to drive the ions over the earth and by their motion produce the effects observed during a magnetic storm.*

We shall tentatively designate the theory which thus aims to account for terrestrial magnetic disturbance as "the ionic theory of magnetic disturbances." It is of interest to quote here from Schuster's extremely suggestive paper[3] on the "Diurnal Variation of Terrestrial Magnetism":

> Outbreaks of magnetic disturbances, affecting sometimes the whole of the earth simultaneously, may be explained by sudden local changes of conductivity which may extend through restricted or extensive portions of the atmosphere. I have shown in another place that the energy involved in a great magnetic storm is so considerable that we can only think of the earth's rotational energy as the source from which it ultimately is drawn. The earth can only act through its magnetization in combination with the circulation of the atmosphere, so that magnetic storms may be considered to be only highly magnified and sudden changes in the intensity of electric currents circulating under the action of electric forces which are always present.

How can we account, on the basis of the "ionic theory," for the velocity of motion of magnetic disturbances and, hence, for the time required to make a complete circuit of the earth? Starting from the well-established law as to motions of ions in gases, it is found that in

[3] *Phil. Trans. R. Soc., A,* Vol. 208, 1908, 184–185.

an electric field of one volt per centimeter (the average potential gradient found from atmospheric electricity observations on the surface), the velocity of the ions would at the height of about 75 kilometers or 47 miles be such that a complete circuit of the earth could be made in 3¾ minutes. Preliminary calculations show that at that height the existent electromotive force may be on the same order as actually assumed in the calculation. The height of 75 km. is about the average of that to which polar lights are seen. We thus place the electric currents, which may produce our magnetic disturbances, at a height where we know, from polar lights, electric currents actually exist.

Should the currents get lower down, then since their velocity varies inversely with atmospheric pressure, they will travel more slowly and the time required for a complete circuit of the earth is correspondingly increased. Their actual effect on a magnetic needle is, however, increased as they get nearer the surface. Hence we may say that the nearer a current gets to the earth's surface, the greater, in general, the disturbance effects and the slower the rate of propagation—this is in accordance, as we have seen, with actual observation. It seems probable that the reason for the remarkably large effects experienced during the magnetic disturbance of September 25, 1909, must be ascribed chiefly to the fact that the currents generated succeeded in getting closer to the earth than for the average magnetic storm.

It is thus seen that on the basis of the ionic theory of magnetic disturbances it is possible not only to explain, in a perfectly natural manner, why magnetic storms do not begin at absolutely the same instant of time over the earth, but also to account for the direction of propagation and the reason for the possible different rates of progression. Thus far, however, the examination has applied exclusively to the sudden beginnings of disturbances or to the simple disturbances characterized by Birkeland as "equatorial perturbations," which our analysis has shown to be chiefly due to a simple, uniform magnetic or electric system superposed upon the existing field. It seems probable that for this class of disturbances, the electric currents producing them are farthest away from us, *i. e.*, they are in the stratum of the atmosphere where their velocity is

such that a complete circuit of the earth, *if made*, would require from 3 to 4 minutes. In this connection it is worth while to record that, judging from Dr. van Bemmelen's observations at Batavia, Java, this interval of 3 to 4 minutes is also the average duration in general of the "starting impulse" at any one station.

After an interval of 3 or 4 minutes, the current either dies out or gets so far away as not to produce any effect. But it may also develop into a steady current continuing for an hour or more and then break out anew into a second starting impulse and finally develop into a complex current system with principal and secondary current vortices, as shown by the more complicated cases of magnetic disturbances.

Professor E. E. Barnard, a member of this society, has recently published[4] for the period 1902–09 a most valuable series of auroral observations made at the Yerkes Observatory from which we quote as follows:

> The streamers which spring from the arch as a base, and which always have a decided lateral motion and last for a minute or so only, almost always move to the west. On several occasions, however, I have seen them divide the arch, with respect to their motion, so that the ones to the west moved west and those to the east moved east. This is very rare. The motion is about 2° in one minute (and not 2 minutes to the degree as I stated in *Astrophysical Journal*, vol. 16, 143). I have wished to determine this motion more accurately, but we have had so few ray-producing auroras in late years, and the rays are so transient, that I have not been able to do so. It would be interesting to know if this motion is constant in a streamer and for all streamers.
>
> The pulsating bright masses that usually appear in the northeast or northwest, but which are sometimes seen under the pole, are among the most interesting phenomena. They are sometimes present when there are no other evidences of an aurora.

If the motion of the streamers is at the rate of 2 degrees in one minute, it would take five to ten minutes or more for the motion to traverse a band from ten to twenty degrees wide. Now the possibility of such a slow motion is contrary to what the cathode ray theory with charged particles moving on the order of 60,000 miles a second would premise, but it is in strict accordance with the results announced regarding the non-simultaneity of magnetic disturbances and their rate of progression over the earth.

[4] *Astrophys. Jour.*, Chicago, Ill., Vol. 31, 1910, 208–233.

According to the theory of magnetic disturbances as set forth above, the various manifestations of solar activity with their resulting emanations and radiations are not the direct but the indirect cause of the earth's magnetic storms. Their effect appears to be more in the nature of a releasing or trigger action, setting in operation forces already in existence in the upper regions of the atmosphere; terrestrial sources, in reality, however, supply the energy required for a magnetic storm. To connect then the well-established, general relationship between magnetic disturbances and the sunspot period, we must suppose that the radiations which alter the conductivity of the atmosphere vary in their amount and intensity in accordance with the periodicity of the solar phenomena.

In the above theory of magnetic disturbances we had to depend on an already existing electric field. If we analyze the results of magnetic observations made at various points over the earth's surface, it is found that about 95 per cent. of the measured magnetic force can be accounted for by an internal magnetization of the earth or by an equivalent electric current system in its interior. The outstanding 5 per cent., however, can only be due to an electric field in the atmosphere.

A preliminary examination discloses the possibility that these atmospheric electric currents may be ascribed to Foucault, or eddy currents, induced in the more or less conducting layers of the atmosphere as, during its general circulation around the earth, the air currents are made to cut across the earth's lines of magnetic force.

The general atmospheric circulation consists in the main of two great atmospheric whirls, the one in the middle and higher latitudes of the northern hemisphere whirling around the north pole in a counter-clockwise direction supposing we are looking down on the north pole. A similar whirl exists in the southern hemisphere except that, if we could look down on the south pole we would see that the whirling is done in the clockwise direction. Could we, however, look at the two whirls in the same direction, for example, from the south pole to the north pole, then the motion would be in the same direction for both, viz., clockwise.

Between the two main whirls, which we shall designate as the "polar whirls," there is another—"the equatorial whirl"—the motion of which is anti-clockwise looking again from the south pole to the north pole the air currents (trade winds) blowing westwards. And, as known, on each border of the two sets of whirls, there exists a belt of high barometric pressure. The direction of motion of the air in the whirls is conditioned by the deflecting effect of the earth's rotation on the air-currents, which are primarily set in motion because of the temperature differences between the polar and the equatorial regions.

Considering first the polar whirls, since the air in them has a motion relative to that of the earth, having a greater velocity than that of the earth's rotation, the currents of air are made to cut across the lines of magnetic force, and that too in the regions of the earth where the most effective induction component—the vertical component of the magnetic force—is strongest. The electric currents thereby induced would, in general, follow a direction at right angles to the motion of the conducting air currents. Consulting a chart of the winds for various seasons, it is seen that the precise distribution of the induced electric currents will be rather complicated. In fact the determination of the exact course of Foucault currents is, in any case, not a simple matter. The displacement of the magnetic axis of the induced electric current system with reference to that of the earth, as dependent on the relative magnetic permeability of the two media involved, introduces another factor to be taken into account.

Since the equatorial atmospheric whirl is opposite to the polar ones, the Foucault negative currents, if brought about, would, generally speaking, be reversed and go around the earth in an opposite direction to the polar negative currents. But the equatorial currents cut the vertical component of the earth's magnetic force in regions of small vertical force, which in fact reduces to zero over the magnetic equator, hence they are considerably weaker than the polar ones. Their strength is further diminished by the fact that in the upper equatorial regions the whirl may be reversed (the anti-trades) and so there would be superposed on the surface equatorial electric currents a set of opposite electric currents.

Hence, as a first approximation, we may confine ourselves chiefly to the polar atmospheric electric currents. Owing to the direction in which they go—approximately southwest to northeast, if negative ones, and reverse for positive currents—it follows that their effect on a compass needle placed on the earth's surface is similar to that of the earth's own magnetism. Or, in other words, the magnetic system equivalent to the atmospheric electric system is precisely similar to that of the earth and the magnetic axis of the atmosphere is hence in the same general direction as the earth's.

There is this difference, however, between the two magnetic fields of the earth and of the atmosphere, viz., that while their north magnetic poles are both in the northern hemisphere, that of the earth is below the surface, whereas that of the atmosphere is in the regions above; hence, while the effects on the compass needle are the same for both, the effects on the dip needle are opposite. The earth's field makes the north-seeking end of the needle dip below the horizon in the northern magnetic hemisphere, whereas the magnetic field of the atmosphere, were it alone acting (the earth's field being eliminated) would make the north-seeking end of the needle point above the horizon. Hence the effects of the two fields on the vertical magnetic component are opposite in the same hemisphere.

In accordance with the well-known laws of induced magnetism or electricity, the atmospheric magnetic field would have to be related to the earth's own field in the following manner: First, the strength of the induced electric currents must be directly proportional to the earth's intensity of magnetization, the electrical conductivity of the atmospheric layers in which the currents flow, and the velocity of the air-currents; secondly, the magnetic axis of the atmospheric electric field must suffer a displacement with reference to the earth's magnetic axis in a direction opposite to that of the earth's rotation (since the earth is moving more slowly than the air-currents); hence, the atmosphere's north magnetic pole would have to lie west of that of the earth's. The angle of displacement depends upon the same quantities as did the strength of the currents, different functions, however, being involved; it cannot exceed 90°.

Examining the results to date from actual observations, a general agreement is found with the hypothesis—the electric currents in the atmosphere not only follow the general direction prescribed, but have a magnetic field whose axis is actually found displaced from that of the earth through an angle of 32° to the west and south. If we examine into the various effects of the primary electric field, many of the phenomena disclosed by the observations in atmospheric electricity, *e. g.*, relation to barometric changes, give additional support to the theory above set forth.

The mechanical effect of the currents induced in the atmosphere will be to increase the velocity of the earth's rotation or more likely to cause a displacement of the earth's magnetic axis eastward. We thus have introduced one of the several systems which together cause the secular variation of the earth's magnetism. This subject, as well as the conversion of electrical into thermal energy and the possible meteorological consequences thereof cannot be entered into here. So likewise mere reference can be made to the subject of the possible vertical earth-air electric currents, which the theory discloses and which I have already partially investigated. Thus far only the effects of the primary circulation of the atmosphere have been considered; manifestly there will be other effects from the secondary motions of the atmosphere.

If the primary atmospheric electric field is brought about electro-dynamically as explained, then it is reasonable to suppose that any periodic or spasmodic fluctuation in the general motions of the atmosphere will result in a corresponding change in the electric field, which in turn may give rise to a variation observed in terrestrial magnetism and atmospheric electricity. Now Schuster had previously shown that the diurnal variation of the earth's magnetism corresponded precisely to what would result from Foucault currents electro-dynamically induced by the daily oscillatory movements of the atmosphere with reference to the earth's lines of magnetic force. The motion of the air currents it was necessary to suppose for the production of the electric currents corresponded precisely to that as indicated by the diurnal oscillation of the barometer. To explain the difference of the effects on the magnetic needle between summer

and winter Schuster had to make the plausible hypothesis that the conductivity of the atmospheric regions was altered in the course of the year by the variation in the supply of the ionizing agencies coming from the sun. Schuster's currents are accordingly the diurnal variation of those of our primary atmospheric field on which we must depend, coupled with the earth's rotation, to furnish the actual supply of energy required to produce and maintain a magnetic storm.

The hypothesis above advanced for the formation of the primary atmospheric electric currents must, at present, be regarded as a tentative one. The precise determination of the characteristic features of this electric field cannot be attempted until the completion of the general magnetic survey of the globe. It ought to be pointed out, however, that the theory advanced to account for our magnetic disturbances is in no wise dependent upon the correctness of the hypothesis as to the origin of the primary electric field. While we do not know, at present, all we should like, we are sure of the existence of this field and that is all the theory requires.

In conclusion let me give you briefly another result obtained from our analysis of magnetic disturbances, viz., that as to the earth's magnetic permeability of which we have had thus far no knowledge. Taking the magnetic permeability of air as unity, it is found that for magnetizing forces on the order of 1/10,000 part of a C.G.S. unit, the earth's average magnetic permeability is about 2. The probabilities are that this value may be somewhat increased as the analysis progresses.